

**TASK DIFFICULTY ASSESSMENT: A Contribution Towards  
Improved Buildability Through Simplification**

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De Montfort University for the degree of Doctor of Philosophy

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## **INTRODUCTION**

*In the construction industry, it has long been a common belief that the planning of construction methods is a subject that cannot be taught - only learned by experience.*

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## **ABSTRACT**

The assessment of buildability within the UK construction industry has typically been carried out on the basis of personal expertise, within which there may be many subjective considerations. This thesis examines the possibility of assessing buildability on the basis of objective criteria, and in an automated manner. A particular problem for buildability to address is identified as the UK construction industry's fragmented nature, particularly the separation between design process knowledge and construction process knowledge. The thesis identifies this separation as commencing during the Renaissance.

The thesis examines a number of possible bases for the assessment of buildability, and concludes that task difficulty appears to be the most suitable basis to meet the objectives of the thesis. Various methods of assessing task difficulty in industries other than construction are evaluated, but none are found to be directly transferable to the assessment of difficulty within construction tasks. No pre-existing methods of assessing task difficulty within the construction industry were identified. The possibility of assessing buildability through an objective assessment of task difficulty measured in terms of operative skill represented within skill models is evaluated. Such skill models represent a new contribution to knowledge.

The success of skill models is found to depend upon the application of general tolerance requirement theory, which supports the buildability attribute of tolerance requirements. Other buildability attributes are identified, but not examined in detail. The effect of various approaches to identifying and counting tolerance requirements on buildability assessment is considered and an algorithm is developed to guide the process.

The research shows that objective assessment of buildability on the basis of tolerance requirements is possible, and that this can be carried out within a CAD environment at sketch design stage in an automated manner using a generic task approach to skill modelling.

## INTRODUCTION

*In the construction industry, it has long been a common belief that the planning of construction methods is a subject that cannot be taught - only learned by experience.*

[Illingworth (1993)]

The research carried out during the completion of this thesis is largely a continuation of an unresolved question raised during earlier research completed to fulfil the requirements of the author's first degree [Moore (1990)]. The unresolved question was: why did consideration of difficulty in construction processes not appear to be formalised within the design process. This question was raised during research examining the hypothesis that there was a link between degree of difficulty for a given task, and the level of quality control required to satisfactorily complete that task. Research was focused on the roofing industry, particularly on tasks involved in covering pitched roofs, and involved consideration of a simple assumption: operatives in the construction industry are not indifferent to the quality of their work. If this was indeed the case, why was the construction industry continuously being criticised for the quality of its product? One possible factor suggested was that, to an undetermined extent, operatives were being asked to produce artefacts which were either completely impossible to build without some variation occurring, or could only be built with considerable difficulty. The resultant quality of a product composed of such artefacts would inevitably be compromised.

Without having some consistent and objective means of assessing the level of construction difficulty inherent in producing a particular artefact, preferably prior to attempting production, then the validity of the above factor could not be

determined. This problem has been found to consistently thwart the various buildability strategies which are proposed from time to time. Within this thesis the problem of consistent and objective buildability assessment is addressed through the development and evaluation of a proposed assessment technique.

The assessment of buildability within the UK construction industry has typically been carried out on the basis of personal expertise, within which there may be many subjective considerations. This thesis examines the possibility of assessing buildability on the basis of objective criteria, and in an automated manner. These two considerations represent the initial boundaries of this programme of research. A particular problem for buildability to address is identified as the UK construction industry's fragmented nature, particularly the separation between design process knowledge and construction process knowledge. The thesis identifies this separation as commencing during the Renaissance. It is important to note that there is no intention within this programme of research to suggest and develop new standard forms of contract, construction technologies or organisation structures in an attempt to overcome this separation. Rather, the intention is to test the following hypothesis:

The production of a skill modelling based automated design aid (ADA), to be used at CAD design stage, would allow task level buildability to be achieved through managing the communication of appropriate knowledge from construction process knowledge workers to design process knowledge workers ie *simplification*.

## Research Methodology

Within the context of the above hypothesis the problem of separation is examined predominantly at the micro, or task, level with respect to what is

appropriate knowledge regarding the process of construction to communicate to design process workers. Chapters two and three, however, commence examination of the problem by considering the construction industry at a macro level in order to set the overall context of the buildability problem, and from this point the methodology applied is one of progressively focusing the research on the problem of identifying appropriate knowledge. The methodology is appropriate to the generic task approach [Chandrasekeran (1988)] which identifies buildability as the problem and then proceeds to the micro level by breaking down the problem into subproblems such as fragmentation, separation, etc. An overview of this methodology is provided as Figure 'A'. The generic task methodology is also used to frame the development of the proposed automated design aid.

The thesis examines a number of possible bases for the assessment of buildability, and concludes that task difficulty appears to be the most suitable basis to meet the objectives of the thesis. Various methods of assessing task difficulty in industries other than construction are evaluated, but none are found to be directly transferable to the assessment of difficulty within construction tasks. No pre-existing methods of assessing task difficulty within the construction industry were identified. The possibility of assessing buildability through an objective assessment of task difficulty measured in terms of operative skill represented within skill models is evaluated. Such skill models represent a new contribution to knowledge.

The success of skill models is found to depend upon the application of general

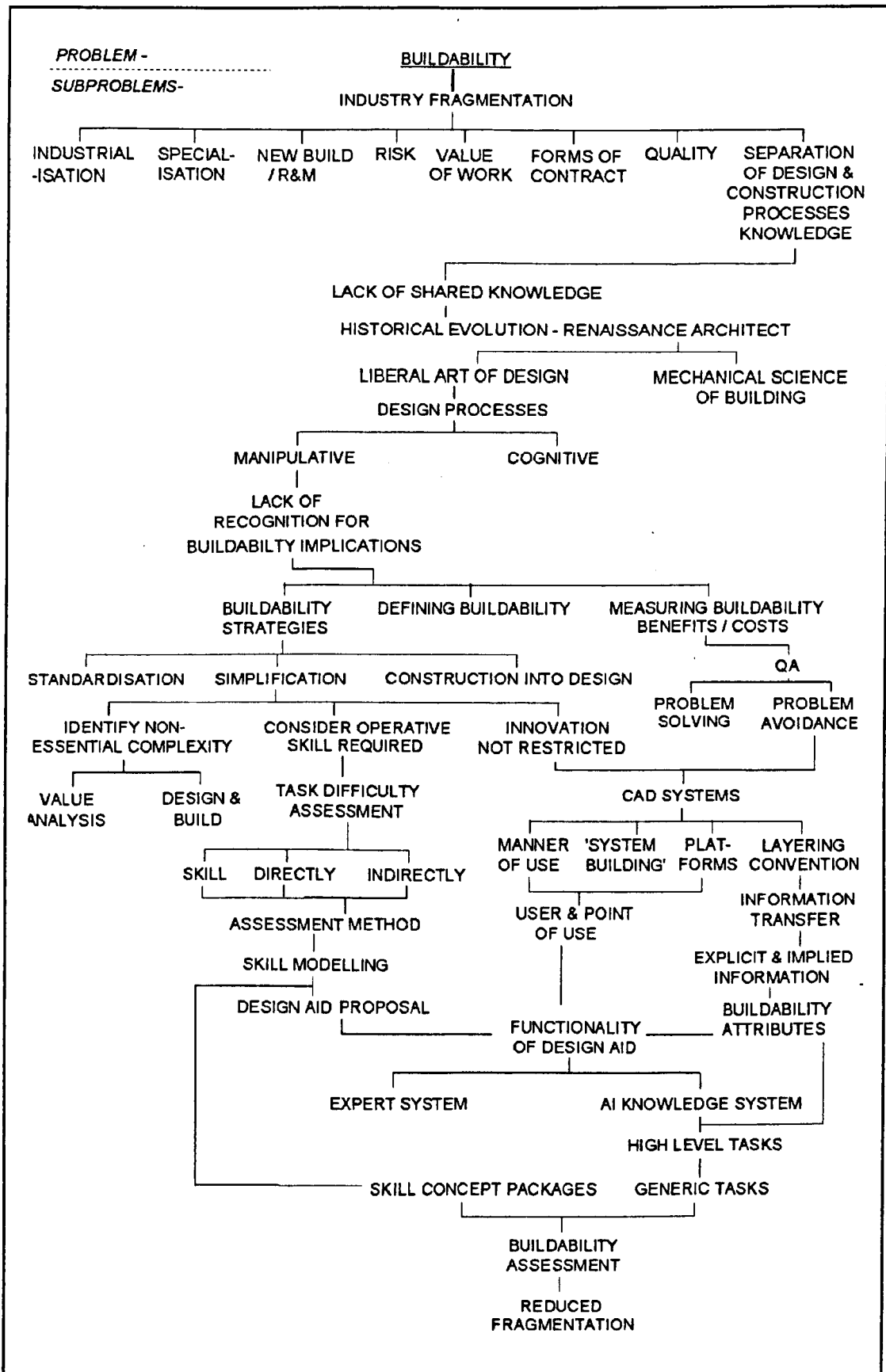


Figure 'A'. Map of key subject areas covered within the thesis.



tolerance requirement theory, as identified by the author, which supports the buildability attribute of tolerance requirements. Other buildability attributes are identified, but not examined in detail, as the tolerance requirements attribute is suggested as being pivotal to the application of the remaining attributes. The effect of various approaches to identifying and counting tolerance requirements on buildability assessment is considered and an algorithm is developed to guide the process. The algorithm has to respond to four production situations, or characteristics, identified by the research: linear uninterrupted; change of direction; isolated; confined. These characteristics are suggested as being sufficient to describe any production situation sufficiently for tolerance requirements to be identified and calculated, and are discussed in more detail in chapter eight.

A key aspect of the work carried out by the author in developing general tolerance requirement theory is the link identified between tolerance requirements and placing time within the above mentioned four production characteristics. Within chapter seven the proposed prototype is developed through the analysis of data resulting from an experiment designed to test the general theory of tolerance requirements (as proposed by the author). The general theory suggests that as the number of tolerance requirements within an area of work increase, the difficulty of completing that work also increases. The nature of the relationship between the two considerations is suggested as being represented by a linear equation. A number of factors which are seen as affecting the form of that equation are discussed, in particular the disciplined development of the experiment used to gather the data from which the equation

is derived. Considerable effort was applied to the experiment's development to control factors which could affect and confuse the data collected. A key consideration in studies related to methods of working is not to carry out unnecessary experimentation, and the small number of timing data are validated on a number of bases.

The essential fact to appreciate concerning the equation is that it is essentially a prototype. This prototype exists to allow testing and development of the key aspects of general tolerance requirement theory, which is suggested as being of a lock-step nature with the further development of the equation, to commence. Any relationship between the constant values within the equation and the expertise of any given individual is argued as being only of value in that it allows the lock-step development process to commence. This is particularly so given that the proposed automated design aid is not intended for use in a programming sense, but is intended for use in comparing versions of a given design for task difficulty as a reflection of buildability. This point is discussed in more detail in chapter seven with regard to the Hawthorne effect.

Tolerance requirement general theory is developed further in chapter eight by focusing on selected characteristics of brickwork artefacts. An experiment is carried out to produce data relevant to the functioning of tolerance requirements within, and adjacent to, the brickwork characteristics of 'confined', 'isolated', and 'change of direction'. Consideration of these characteristics allows the general theory of tolerance requirements to respond to the phenomenon of tolerance requirement overspill. Overspill occurs in the vicinity of characteristics, and is

effectively a requirement to double count certain tolerance requirements.

Chapter nine provides a number of conclusions regarding the research completed by the author, and also suggests suitable areas for further research on, and development of, the prototype automated design aid.

The research shows that objective assessment of buildability on the basis of tolerance requirements is possible, and that this can be carried out within a CAD environment at sketch design stage in an automated manner using a generic task approach to skill modelling.

In completing this research the author became aware of the problem that terminology tends to be used loosely, and at times in a contradictory manner, with the consequence that existing terminology was not always appropriate to the research being carried out. It was therefore found necessary to define new terms, and resultant acronyms, on a number of occasions. All such terms are italicised on their first use, and a glossary of terms and acronyms is included at the conclusion of this introduction.

Within the research supporting this thesis the author has attempted to deal with the problem of buildability being perceived as either a vague, ill defined concept, or as a prescriptive, imposed technological solution to the design problem. As a result, a new perspective on buildability has been developed; that of a product which can be defined and potentially assessed on the basis of objective criteria, without resorting to the imposition of specific technological

solutions. Some of the concepts from which this perspective is formed have not been applied to buildability previously, and may therefore seem radical. However, at the risk of seeming a zealot, in carrying out this research, the author has come to the conclusion that only radical concepts offer real solutions to the construction industry's problems.

During the programme of research supporting this thesis, a number of papers were published with the intention of obtaining peer review of the research as it progressed. These papers are provided in full as appendix one for detailed examination. Chapters two to five in particular relate to the subject matter covered by the papers in appendix one, and are therefore effectively concise summaries of them. Reference to the relevant papers is given in each chapter. As a further aid to the reader, Figure 'A' has been produced. This figure provides a 'map' of the key subject areas dealt with by this thesis, illustrating the links between the various areas which may otherwise appear to be isolated chapters.

Within this research the intention is to find a method of assessing, in an objective and automated manner, the task difficulty inherent in constructing given designs. Task difficulty is suggested as being one means of assessing buildability within a construction project. There is no intention within this research to exclude any other means of assessing buildability, and the proposed means of assessment could well be used in conjunction with other means of assessing and/or implementing buildability. Detailed objectives are:

- i) to provide an overview of the complex nature of the UK construction industry; the context within which the proposed design aid must operate.
- ii) to illustrate how the evolution of the design process, with its separation of design and construction processes knowledge, has contributed toward the present day need to consider buildability explicitly.
- iii) to determine the value of buildability strategies in communicating relevant knowledge of construction processes to design process workers.
- iv) to identify and evaluate possible strategies for the development of a buildability assessment model based upon task difficulty as a reflection of buildability.
- v) to determine a means of automating such a buildability assessment model.
- vi) to produce a pre-prototype form of buildability assessment model which utilises the selected strategy and basis for assessment.
- vii) to evaluate the pre-prototype assessment basis through relevant experimentation, and from the evaluation identify further areas of research required to enable progression of the assessment basis to a level suitable for use in a prototype model of buildability assessment.

The primary objective of this research is to descry a possible means of aiding the design process worker to envisage the requirements of on-site production processes in providing a product which meets design requirements. In this manner a contribution toward improved buildability will ensue.

**Accuracy** - The proximity achieved by an operative to the required ideal level of placement within an accepted three dimensional model representing the maximum and minimum tolerances relevant to the assembly process.

**Competence** - The proximity achieved by an operative to achieving all the known rules relevant to the completion of a task.

**Explicit Monitoring** - That time during the process of construction where the operative exhibits monitoring behaviour of an explicit nature, such as use of the level, and no behaviour which could be classed as productive.

**Interfacing** - The manner in which the fixing requirements of one high level task (HLT) interact with the fixing requirements of a second HLT at the point(s) where both HLTs meet.

**Lawful** - Within the rules recognised by the process of decomposition.

**Novice** - Having insufficient previous experience to effectively progress beyond being a passive observer to being an active participant.

**Placing Movement** - A small, slow movement used to locate a component within a subassembly.

**Placing Time** - measured from a point approximately 5% of the travel distance away from the final location of the component being placed to a point at which the placing movement can be reasonably stated as having been replaced by normal productive movements.

**Rapidity** - The proximity achieved by an operative to completion of a task within a duration accepted as being the minimum practically achievable under the conditions in which the assembly process is to be carried out.

**Repetition** - The maximisation of use of the minimum number of materials, components and sub-assemblies.

**Range** - The total number of HLTs required to construct a given design.

**Skills** - All the factors which go to make up a competent, rapid and accurate performance.

**Tacit Monitoring** - Monitoring behaviour of a non-explicit nature which does not interrupt the process of construction.

**Task Difficulty** - The extent to which the exercise of the *Skill* components of *Accuracy*, *Rapidity* and *Competence* is required in order to complete a given task.

**Tolerance Requirements** - The defining of a given productive action in terms of predetermined plumb, level, and square quality criteria. These criteria to be expressed in terms of x, y, and z co-ordinates.

**TR overflow** - A situation occurring when future and past TR overflow into consideration of work in progress.

Figure 'B'. Terms having a specific meaning within the thesis.

ADA -	Automated Design Aid
A,R,C -	Accuracy, Rapidity, Competence
CAD -	Computer Aided Design
CAWD -	Computer Aided Workplace Design
DAC -	Design Assisted by Computer
GT -	Generic Task
GTd -	Generic Task Difficulty
GTdA -	Generic Task Difficulty; Accuracy
GTdR -	Generic Task Difficulty; Rapidity
GTdC -	Generic Task Difficulty; Competence
HID -	Human Integrated Design
HLT -	High Level Task
JSI-	Job Severity Index
KBS -	Knowledge Based System
NIOSH -	National Institute of Occupational Safety and Health (USA)
RWL-	Recommended Weight Limit
SCoP -	Skill Concept Package(s)
Td -	Task Difficulty
TR -	Tolerance Requirements

Figure 'C'. Acronyms used within the thesis.

## **1. FRAGMENTATION IN THE UK CONSTRUCTION INDUSTRY**

*The construction industry has literally built Great Britain. Its activities are concerned with the planning, regulation, design, manufacture, construction and maintenance of buildings and other structures.*

[Harvey, Ashworth (1993)]

The UK construction industry plays an important role in the economic activity of the country as a whole, as illustrated in section 1.3 where figures relevant to the value of the construction industry are presented. Within such an industry there is potential for inefficiency and wastage. However, the construction industry exists as more than just a contribution to economic activity; the construction product also serves other functions, as is discussed in section 1.2.

### **1.1 The Industry and Fragmentation.**

Any examination of the complex nature of production within the construction industry, has to be contained within certain boundaries. In broad terms the industry can be seen as being composed of building, civil engineering, and process-plant sectors [Harvey, Ashworth (1993)]. The industry, however, is generally seen as possessing a high level of fragmentation. "The UK construction industry meets the demands upon it through the actions of a large number - well over 115,000 - business units or firms.." [Hillebrandt (1985)]. The nature of this fragmentation varies over time in response to factors external to the industry. Figure 1 shows how the nature of fragmentation, in terms of numbers of construction firms of given size groupings, has changed over a twenty year period.



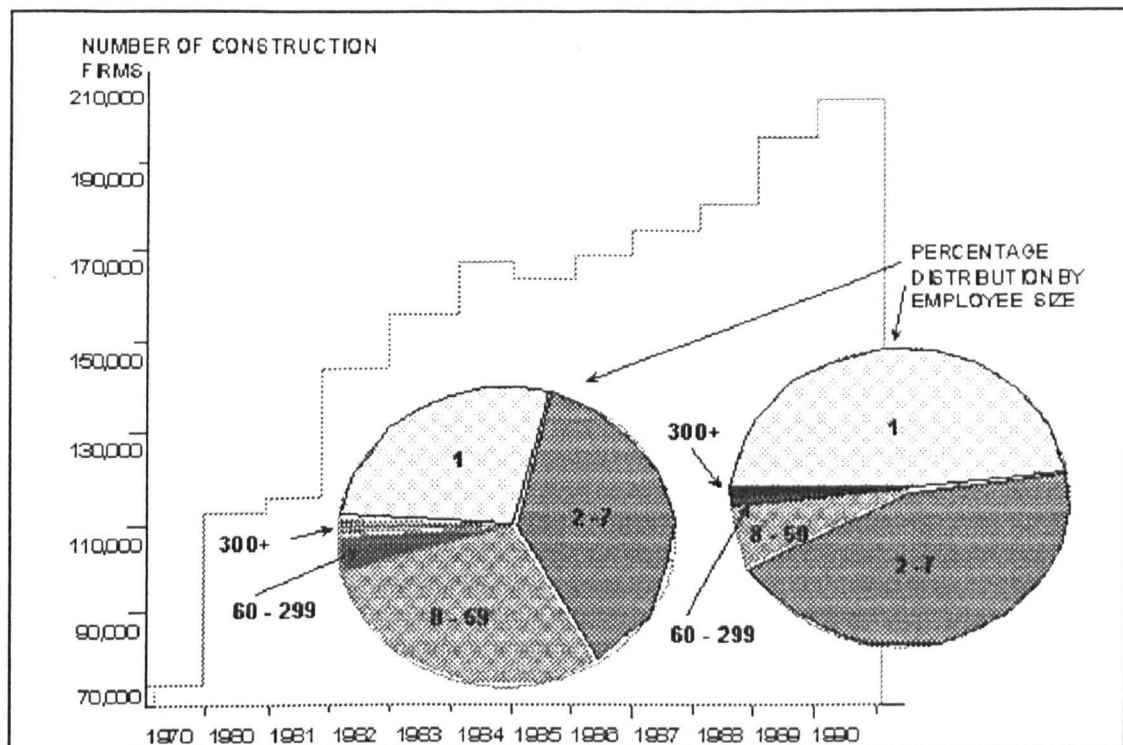


Figure 1. Fragmentation in terms of numbers of construction firms.  
[Harvey, Ashworth (1993)]

The change has been in the form of an increase in the number of small firms, particularly sole proprietors, in the industry and a decrease in the number of medium to large firms. Both of these changes have repercussions for the manner in which the industry operates: there is growing concern amongst clients that large firms operating as contractors may lack the capacity to take on contracts of £25m+, as one example. Consequently, there may be only three or four of the top ten UK contractors who are likely to be put on bid lists for such contracts [Building (1995a)]. Such a situation is unlikely to be of benefit in maintaining a broad base of production process expertise within the industry. The author suggests therefore that the role of buildability, particularly in the context of communicating knowledge, will become an increasingly important one, should the expertise base continue to diminish.

1.1.1 *Specialisation.* Part of the changing fragmentation profile can be accounted for by the increased numbers of self employed persons within the industry as construction seeks to become a more 'flexible' industry. Figure 2 shows the rate of change in manner of employment, and also the overall level of employment over the period 1987-1994.

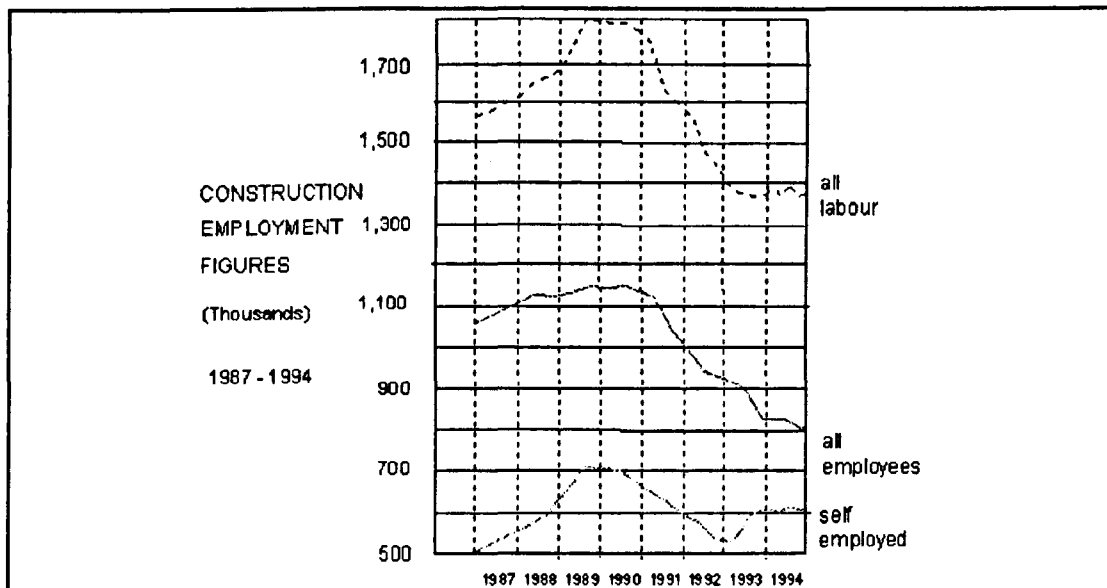


Figure 2. Rate of change in directly employed and self employed. 1987-1994. [Construction Monitor (1995a)]

A further aspect of this 'flexibility' is the range of different trades and professions within the UK industry. A relevant point is that there are no legal requirements relating to the use of the titles of 'surveyor' or 'engineer', and the UK legal system does not seek to restrict anyone from practising these professions, whereas the architect has a title defined by law [Chapman, Grandjean (1991)]. This situation has possible repercussions for any assumptions made regarding the level of expertise which can be expected of someone using a title other than 'architect'. Whilst this may cause problems in

general it is of little significance regarding this research due to:

- a) the proposed prototype design aid is not intended for use by anyone other than a design professional (architect).
- b) there is no intention to use the proposed design aid for instruction of design professionals in the process of design, as opposed to construction.
- c) no specific assumptions are made regarding the design professional's level of expertise regarding the process of construction.

FIRM CLASSIFICATION	NUMBER OF FIRMS	FIRM CLASSIFICATION	NUMBER OF FIRMS
General Builders	78,981	Heating & ventilating	9,624
Building & civils	4,773	Electrical	20,732
Civil engineers	3,742	Asphalt	1,080
Plumbers	17,046	Plant hire	4,628
Carpenters & joiners	15,244	Flooring	1,999
Painters	16,511	Construction	
Roofers	7,767	engineers	2,592
Plasterers	4,834	Insulating specialists	1,376
Glaziers	6,531	Suspended ceilings	1,554
Demolition		Floor/wall tiling	1,657
contractors	667	Miscellaneous	6,003
Scaffolders	1,524		
Reinforced conc. specialists	910	<b>TOTAL</b>	<b>209,793</b>

Figure 3. Classification of firms by trade of firm: 1990  
[Summarised from Harvey, Ashworth (1993)].

Figure 3 illustrates the range of trade firms within the industry, and the contribution of each type to the overall composition of this industry sector in 1990. This illustrates the range of differing skills required by the modern construction industry. Such a range is greater than at any previous point in the history of the industry [Moore (1996b)]. Furthermore, the constituents of the range vary over time as old technologies diminish and new technologies are

introduced [Harvey, Ashworth (1993)]. As a consequence of this, controlling the construction process can be problematic.

**1.1.2 Unique characteristics.** These are summarised in Figure 4. Of the identified characteristics, the author suggests that numbers three, four and five are of greatest significance to this research. Number four specifically is noted frequently throughout the literature as being an important factor regarding the achievement of good buildability.

1.	The physical nature of the product.
2.	The product is normally manufactured on the client's premises, ie the construction site.
3.	Many of its projects are one-off designs, and lack any prototype model being available.
4.	The arrangement of the industry, where design has normally been separated from construction.
5.	The organisation of the construction process.
6.	The methods used for price determination.

Figure 4. Unique characteristics of the construction industry.  
[Harvey, Ashworth (1993)].

## **1.2 The Built Environment; the construction product.**

All who inhabitant the built environment are also users of the construction industry product. It can be argued that "Building technology cannot be isolated from the society in which it is practised and developed." [Chandler (1987)]. This argument is supported by a number of invariably economic factors, such as employment for skilled and unskilled labour, creation of the transport systems, energy supply networks and other requirements of a developed society's

infrastructure. In short "Construction is important in any developed and dynamic society" [Chapman, Grandjean (1991)].

1.2.1 *Good and bad products.* Building technology functions within a society in terms of a framework composed of eight sections, such as functional requirements, safety aspects, available resources, design, technological change and development, etc. [Chandler (1987)]. Within this programme of research each of these factors do not require equal emphasis, but can be seen as contributing towards the assessment of a product as being 'good' or 'bad'. A 'good' product can enhance our existence, whereas a 'bad' product is capable of detracting from our quality of life. Such considerations are outside the scope of this programme of research, which concerns itself only with good or bad buildability within the context of construction processes of production.

Good buildability should not be achieved at the expense of due consideration for the creative aspect of the product. The human animal in general has some need to indulge in the practice of creativity, which is seen as being an important constituent of the process of designing a solution to the problem of what is to be built [Moore, Tunnicliffe (1994a); (1994b)]. An example of this process is the Sydney Opera House, where the desire of the architect to achieve a particular aesthetic drove forward research in areas of building technology [Smith (1993)].

1.2.2 *Society demands.* Society puts demand to the construction industry for investment goods, the ultimate use of which may be:

- a) as a means of further production, e.g. factories

- b) as an addition to or improvement of the infrastructure of the economy, e.g. roads
  - c) as social investment, e.g. hospitals
  - d) as an investment good for direct enjoyment, e.g. housing.
- [Hillebrandt (1985)]

The construction industry exists to meet the demand for products, in whatever form, put to it by society. The ultimate use of those products is suggested by the author as being irrelevant to this research, in so much as the designer has responsibility for the interpretation of user requirements in the development of a design [Salisbury (1990)]. The primary objective of this research is to determine the possibility of aiding the designer in understanding the needs of on-site production processes in providing a product which meets user requirements, rather than aiding in the interpretation of user requirements.

Society is generally becoming more concerned that industries should operate 'ethically', one aspect of which is operating in a sustainable manner. Aspects of the ongoing debate regarding sustainable construction have been examined elsewhere [Moore, Ahmed (1995)]. However, elimination of avoidable costs is a task upon which the construction industry is increasingly focusing. It has been stated that rectifying faulty work in defective buildings accounts for about 15% of the industry turnover [Building (1995b)]. Good buildability has a contribution to make in the reduction of costs, and thereby conservation of resources, related to rectifying faults in defective buildings, both during and after construction.

**1.2.3 Repairs and maintenance sector.** Two main sectors exist within the industry; new build, and repairs and maintenance. The balance between these

two sectors varies over time. As a general rule, the level of repairs and maintenance (RM) activity increases as demand for new build decreases. Typically RM accounts for 40-45% of the value of work carried out by the industry. Figure 5 shows the breakdown of figures for the period 1991-1994.

YEAR	ALL WORK (£bn)	RM (£bn)	RM AS % OF TOTAL	RM AS HOUSING (£bn)	RM AS 'OTHER' (£bn)
1994	50.079	20.843	41.6	11.784	9.059
1993	48.555	19.973	41.1	11.236	8.737
1992	49.522	20.470	41.3	11.368	9.102
1991	51.561	21.919	42.5	12.182	9.737

Figure 5. Repairs and maintenance sector 1991-1994  
[Abstracted from Construction Monitor (1995b)].

This split is not a problem with regard to application of buildability at the design stage. No evidence has been identified within the literature which suggests that a buildability strategy of the type proposed by the author would be of greater, or lesser, relevance to either of the sectors.

### 1.3 Value of the industry

Figure 6 illustrates one measure of the industry's value; the total construction industry output per annum. In order to put these levels of output into context; within the British economy, the industry typically accounts for 6% of Gross Domestic Product (GDP) and provides over half of Britain's fixed capital investment; within the European economy, the British industry is fourth largest, behind Germany, France and Italy, accounting for 10% of production

[Chapman, Grandjean (1991)]; within the global economy the industry generally obtains work worth several billion pounds annually [Harvey, Ashworth (1993)].

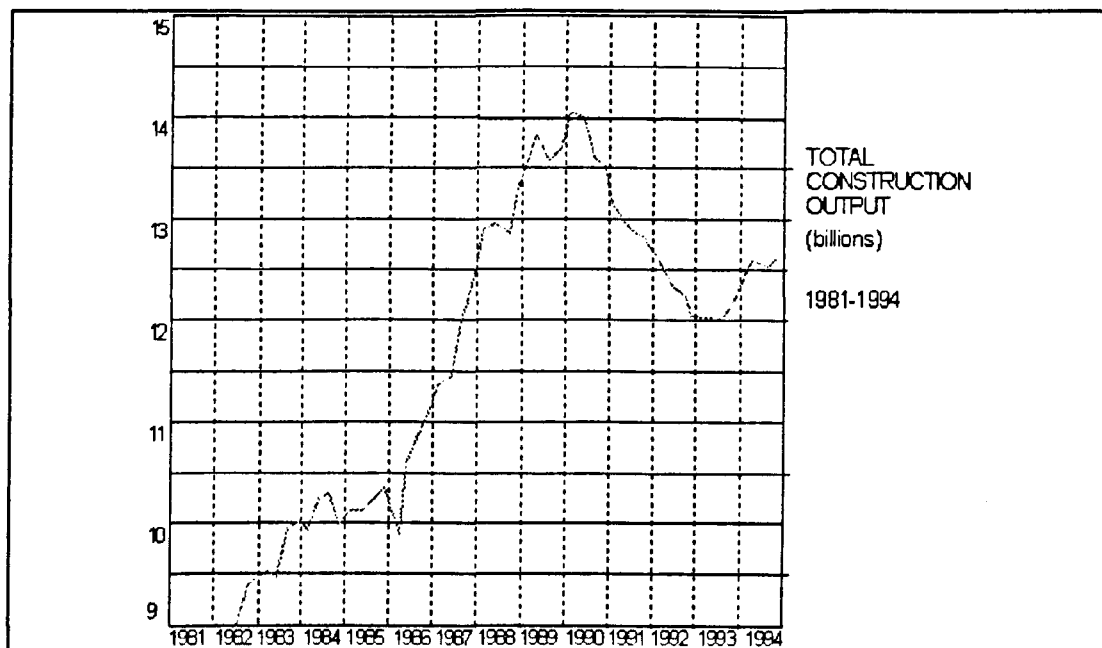


Figure 6. Total UK construction industry output: 1981-1994; quarterly figures. [Construction Monitor (1995c)]

Within an industry of such financial value even relatively small, in percentage terms, improvements in efficiency can result in large monetary savings for the industry as a whole. The possible benefits of improved buildability are examined in more detail in chapter four, but it is worth noting at this point that even the worst projections for possible savings resulting from improved buildability [Gray (1983)] would result in annual savings of approximately £500,000,000.

#### 1.4 Organisation of the industry; Forms of Contract

The fragmentation problem can be argued to have resulted in an industry which is difficult to control effectively; a problem which has been addressed to some



extent through the development of a number of standard forms of contract. There is no single overall standard form of contract utilised by the industry. The predominant standard form is the Joint Contract Tribunal (JCT) series.

Standard Form Type	Use by Number (%)	Use by Value (%)
JCT 80	25.83	44.22
JCT 63	5.22	2.72
MINOR WORKS	28.55	2.58
IFC84	16.45	8.20
DESIGN AND BUILD	4.31	10.58
MANAGEMENT	1.20	14.59
CONSTRUCTION MANAGEMENT	0.19	6.71
OTHER FORMS	18.25	10.40
<b>TOTALS</b>	<b>100</b>	<b>100</b>

Figure 7. Standard Forms of contract: extent of use 1989. [RICS (1991)].

Figure 7 gives the main forms of contract and the extent of their use as determined in a 1989 survey carried out for the Royal Institute of Chartered Surveyors [RICS (1991)]. This survey excluded Repairs & Maintenance (R&M) projects and work carried out by contractors without the involvement of consultants. Even with such omissions the situation is potentially a complex one, frequently requiring the services of a further specialist; the construction legal adviser.

1.4.1 *An adversarial industry.* The construction industry is generally

regarded as being adversarial in nature. This has various repercussions for the industry in areas such as training, R&D, lack of teamworking, and a general unwillingness to be innovative. These all combine to affect the efficiency of the industry in a negative manner. Working Group 11 (WG11) of the Review Implementation Forum (RIF) noted that the adversarial nature of contracts can have a medium rated impact on the avoidance of costs in the general area of 'conflict'. WG11 also noted that lack of trust and teamwork within the industry can have an impact rated as high on avoidable costs within the general area of waste and duplication [WG11 (1995)].

The UK industry's adversarial nature is exemplified in a comparison carried out by the author between the JCT 80 form of contract, and its equivalent in Denmark; AB 72. Denmark was selected because its construction industry is generally held to operate on the 'family' approach to organising relationships between firms. The result being a high level of trust and a willingness to become involved in long term relationships. The Danish industry also employs a broadly similar percentage of the population, and contributes to GDP in similar figures, as does the UK industry [Chapman, Grandjean (1991)].

The nearest Danish equivalent to JCT 80 was suggested by Professor Bjørn Bindslev of The Royal Academy of Fine Art in Copenhagen as being *Almindelige betingelser 1972* (AB 72). As a comparative overview of the two standard forms, Figure 8 provides an enumeration of the sections and subsections within both documents. A point suggested as being worthy of note is the relatively small amount of emphasis placed on 'disputes' in AB 72.

<b>JCT 80 MAIN SECTION</b>	<b>No. OF SUB- SECTIONS</b>	<b>AB 72</b>	<b>No. OF SUB- SECTIONS</b>
1. Articles of Agreement	5	1. Basis for Agreements	5
2. Conditions: Part 1	133	2. Execution of the Works Under Contract	4
3. Conditions: Part 2	31	3. Representation and Co-operation	5
4. Conditions: Part 3	23	4. Time Limits	2
5. Conditions: Part 4	1	5. Handing Over the Works	1
6. Supplemental provisions	7	6. Responsibility and Risk Apart From Determination	5
		7. Determination of Contract	2
		8. Financial Matters	5
		9. Disputes	2
<b>TOTAL</b>	<b>200</b>	<b>TOTAL</b>	<b>31</b>
<b>PAGES</b>	<b>68</b>	<b>PAGES</b>	<b>8</b>

Figure 8. Comparison of JCT 80 (Private With Quantities) and AB 72. [JCT (80), AB (72)].

The UK industry has a high rate of litigation, which seems to result from there being relatively little controlling legislation on the industry, and the importance placed upon the contract documents as a means of communication. Vagaries in UK contract law, combined with the wide range of standard forms, which can be freely adapted to one-off circumstances, may be a significant contribution to the fact that in the UK there are around 59,000 'registered lawyers' whilst the figure for France is only around 17,000 [Chapman, Grandjean (1991)]. This situation is added to by the noted preoccupation of the majority of contractors with making a claim on every possible occasion. Such a situation is held to

result from the predominance of competitive tendering as a means of contractors winning work on the basis of the lowest price. The making of claims is one technique for extracting profit from an underpriced contract [Harris, McCaffer (1995)].

The author suggests that such a level of adversarial behaviour adds to the effects of fragmentation noted previously by increasing the resistance to freely flowing information between all parties involved in the construction industry. Schaefer (1993) has noted the problems of managing, and retaining, information in the form of knowledge within construction enterprises and project teams. Working Group 11 [WG11(1995)] has also noted the adverse effects of a lack of teamwork on the level of costs within the industry.

## **1.5 Product and production problems**

The problems which affect the efficiency of production within the construction industry can be summarised under four headings:

**1.5.1 Risk and uncertainty** Competitive bidding based upon the information available in the tender documents is the most common method of deciding which contractor will carry out a given project [Harris, McCaffer (1995)]. Inherent in this process is a degree of risk and uncertainty for all participants. Skitmore (1989) noted that such uncertainties and risks are likely to be major aspects of the project decision problem. One result of the predominance of competitive bidding for the contractors is that they face uncertainty in their long-term planning, adding to the adversarial nature of the

industry discussed previously.

Contractors also face the uncertainty of information, as supplied in the tender documents, being changed once construction commences. The possible effects of different design processes in this respect are discussed in chapter two. Any aid to the design process which potentially reduces uncertainty in the construction process should be investigated. The proposed design aid may prove to have such a potential.

**1.5.2 Quality** Product quality has become an increasingly important consideration in the construction industry, particularly for some clients. This has allowed the concept of quality to evolve through a number of stages as summarised in Figure 9.

STAGE NUMBER	STAGE CHARACTERISTICS.
1.	Inspection, where checking is carried out to make sure that what is produced is what is required
2	Quality control, which introduces checking at various stages of production on the basis of statistical sampling
3	Quality assurance, whereby specifications are consistently met through application of principles such as 'right first time' and 'fit for purpose'
4	Total quality management, in which a philosophy of continuous improvement is introduced to production

Figure 9. Stages of quality concept evolution.  
[Summarised from: Harris, McCaffer (1995)].

There is an argument within the literature that construction standard forms of

contract represent a sufficiently robust quality system within themselves. The validity of such an argument can be gauged against the four provisions of a successful quality system for procurement:

1. precise definition of clients requirements.
2. selection of potential suppliers who can demonstrate the will and ability to meet those requirements.
3. surveillance of work in progress.
4. verification that the purchased products are in conformance with the specified requirements.

[Summarised from Ashford (1989)].

PROVISION	COMMENTS
1. Precise definition	a) specification and drawings subject to practical limitations regarding amount of detail. b) reliance placed upon interpretation of what is required by builder. c) litigation increasingly used when this does not happen, which is indicative of unsatisfactory performance regarding definition.
2. Potential supplier selection	a) two significant suppliers; architect and builder. b) RIBA conditions of engagement stipulate architect's fees to be in accordance with standard scales. c) standard scales do not act as an incentive to control costs as the architect's fee rises with them. d) standard scales also create a conflict of interest in cases of adjudication on claims by contractor for same reason as at c). e) selection of contractors by open selective tendering does not guarantee that the selected supplier possesses the required skills and equipment to complete the work to specification. f) contractors do not have the option to vary specifications in order to offer purchasers better value for money.
3. Surveillance	a) how can a purchaser who is lacking in technical expertise monitor and check the work of the architect or contractor?
4. Verification	a) inspection procedures on site suffer from a lack of clear definition of responsibilities. b) completion of the works is frequently taken as <i>ipso facto</i> proof that checks have been made and satisfied.

Figure 10. Comparison of traditional forms of procurement to the four provisions of a successful quality system. [Abstracted from Ashford (1989)].

Figure 10 summarises a comparison of traditional forms of procurement for construction products to the above requirements. From this it can be seen that traditional forms of procurement are questionable with regard to their suggested operation as quality systems. Particular concern has been expressed by Ashford (1989) regarding the lack of integration between designers and builders, a problem which had been noted previously by others [Emmerson (1962), Banwell (1964), Yamazaki (1992)]. Acknowledgement of this situation has resulted in more innovative forms of procurement such as management contracting and design and build.

The success achieved by innovative forms of contract can be judged to some extent by the recommendations of the consultation document *Constructing Quality*, produced by the Quality Liaison Group (QLG). One of the recommendations in the document is the "Early integration of the whole team's skills and knowledge to be at the core of any procurement strategy" [QLG (1995)], thus suggesting that lack of integration is a continuing problem. QLG also noted there is every indication that defects occurring in the present day industry are little different those occurring twenty years previously [QLG (1995)].

**1.5.3 Time** Late delivery of the construction product is a frequent cause for complaint by construction clients [Moore (1993a); (1995)]. Walker (1989) has suggested that the programme for a project should represent a realistic coordinated plan of the time needed for completion of the project in its entirety. This time should cover the period from the start of the project until the completion of commissioning (if any). However, Walker notes that this is not

always achieved, as the preparation of the programme, ideally during the early design phase is a much neglected area due to none of the professionals involved in the design phase specialising in production of programmes, unless there is a Project Manager present [Walker (1989)].

Ferguson (1989) notes that "Programming must be realistic but challenging" and that buildability is a key factor in achieving this as, irrespective of the method of programming used, the basis is consistent: assessment of the time needed to carry out assembly activities. Assembly time assessments are arguably of most significance in commercial projects. The National Economic Development Office (NEDO) noted that commercial customers for the construction product expect punctual construction times due to the high cost of money and the returns expected from the finished building. Achieving such times depended upon the expertise used, and level of teamwork achieved, in overlapping presite and site operations. Fast track methods were noted as not being able to achieve such times of themselves [NEDO (1988)].

**1.5.4 Cost** The construction industry has problems with respect to cost control which do not normally concern other industries, many of which result from the one-off nature of the construction product. Fresh management teams for each project; transient, *ad hoc* recruited labour, and geographically dispersed sites are typical examples. An important result of these problems is that the majority of construction firms do not use standard cost systems such as are typical of manufacturing firms [Harris, McCaffer (1995)].



This research does not seek to provide definitive projections of the effect on costs resulting from the achievement of good buildability. The possible financial benefit of good buildability has been mentioned previously.

### **1.6 Industrialisation of the industry**

The construction product is large, heavy, expensive, required over a large geographical area, and is generally made specifically to the requirements of each individual customer. A number of the components used by the industry are manufactured by other industries. These characteristics result in an industry structure composed of a large number of dispersed contracting firms predominantly separated from the design process [Hillebrandt (1985)]. This problem can become particularly difficult when considering the use of prefabrication in the production of a building, which can be viewed as a process of industrialising the construction industry. This process is one which may prove to have repercussions with regard to quality, time and cost in the creation of the construction product, but is seen as being of little significance to this programme of research. The proposed design aid will not seek to advise directly on the benefits and disbenefits of an industrialised construction industry, as there are many complex issues within such a debate. However, the design aid will seek to recognise within its philosophy the argument that closed technology systems, such as typically result from industrialisation, are not generally attractive to design professionals.

### **1.7 Legal considerations**

The construction industry has an equal responsibility to that of other industries

to work within those boundaries established by the raft of general legislation governing economic activities. A number of statutes have specific relevance to the construction industry. The most relevant statutes with regard to the subject matter of this thesis are suggested as being those pertaining to health and safety.

**1.7.1 Health & Safety** The industry has long had a bad reputation with regard to safety, despite attempts to reduce the problem through imposition of legislation such as the Health & Safety at Work etc, Act. The most recent legislation of this type are the Construction Design Management (CDM) regulations, which are particularly relevant given the nature of the proposals by the author within this thesis.

**1.7.1.1 CDM regulations.** These regulations aim to improve health and safety for construction industry personnel. The regulations were delayed a number of times due to concerns expressed by the industry, mainly regarding the possible costs of implementation. Such costs were claimed to be attributable predominantly to the creation of two functions new to the industry; planning supervisors and principal contractors. Whilst CDM was placed within the enforcement regime of the Health & Safety at Work etc. Act 1974, the direction taken by the regulations was a preventative one, in that they required the assessment of a structure's design for possible risk to personnel during the whole life cycle of the building; production, maintenance and demolition. This assessment is the role of the planning supervisor, whilst the role of the principal contractor is to oversee development of health and safety plans and ensure the

competence of other contractors onsite.

The relevance of CDM regulations to this thesis is that they place greater emphasis on the scrutiny of designs for possible problems than has previously been the case. Whilst this scrutiny is, at present, for the purposes of assessing risk to operatives, it can only be of benefit with regard to the assessment of buildability. This is seen as arising from the situation where designers, and others, become accustomed to perceiving product designs as being more than a source of information on quantities of materials.

### **1.8 Organisation of the industry; A 'systems' viewpoint**

Whilst an approach of viewing the construction industry from a series of single perspectives has a value with regard to itemising the diversity of the industry, care needs to be taken that a sense of the overall interaction of these aspects is not lost. This interaction can be considered through the technique of viewing the industry in terms of 'systems' of production.

**1.8.1 What is a 'system'?** Miller and Rice (1967) define a system as being comprised of an import, a conversion process, and an export (ICE). The author suggests that such a view of the production process allows the various interactions within that process to be determined in a specific manner. This is particularly so given that a systems approach can be applied at various levels, such as at the level of the firm or enterprise. A further level is at the task, where a task system can be defined as "...a system of activities plus the human and physical resources required to perform the activities." [Miller, Rice (1967)].

Viewing the production process in terms of activities required to convert discrete imports into discrete and singular exports, along with the human and physical resources attendant upon these activities (see figure 11), is suggested by the author as being potentially valuable in focusing upon the explicit production requirements of a given product design.

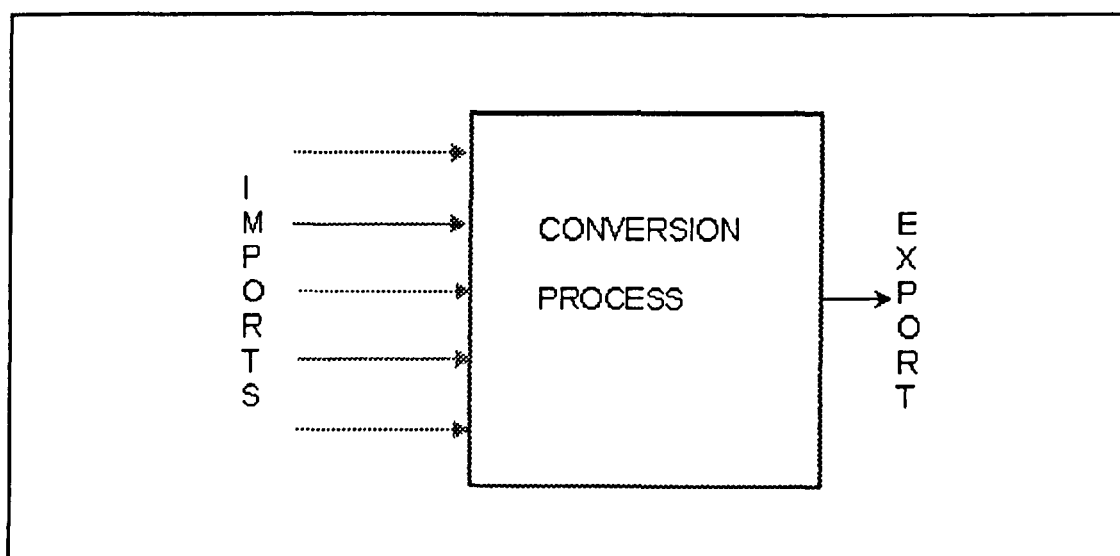


Figure 11. A basic system of production.

## 1.9 Conclusions

The construction industry is a fragmented and complex industry which faces diverse problems, as summarised in Figure 12, in achieving an efficient production process. It is suggested that no single approach to buildability can realistically be expected to solve such a diversity of problems. The difficulties arising from over-ambitious approaches to achieving buildability are discussed further in chapter four, but the author wishes to clearly state at this point that the design aid proposed within this research is focused solely at the problem of separation between the design process and on-site production knowledge.

This research is therefore targeted specifically at those sections of the industry directly involved in the designing of the construction product, irrespective of the nature of that product.

<b>PROBLEM No.</b>	<b>PROBLEM NATURE</b>
1.	The diversity of construction products.
2.	The resultant requirements for specialisation.
3.	The preponderance of small firms caused by specialisation.
4.	The high level of fragmentation caused by specialisation.
5.	The diversity of forms of contract.
6.	The separation of design and construction processes knowledge
7.	Diversity of construction technologies.
8.	Diversity of construction materials and components.

Figure 12. Summary of construction industry problems preventing an efficient production process.

The industry also has to operate within a number of constraints:

1. statutory requirements.
2. common law requirements.
3. society's expectations of an ethical industry.
4. level and diversity of demand for construction products.
5. resource availability (labour, plant, materials, cost, quality, time).

Any attempt to increase consideration of buildability within the industry must recognise the existence of these constraints and work within them. The proposed design aid will therefore seek to address the problem of separation between design and production knowledge. This will be done in a manner which presents an opportunity for design professionals to be creative in meeting

the diversity of demand placed on the industry, whilst also acknowledging the constraint of resource availability.

In order to appreciate the difficulties faced by the construction industry in achieving the production of suitable products, whilst accepting the constraint of resource availability, especially regarding cost, quality and time, detailed examination of the concept of buildability is suggested by the author as being essential.

## 2. BUILDABILITY: A SOLUTION FOR THE INDUSTRY'S PROBLEMS?

*It has long been appreciated that when the information provided to contractors is insufficient, conflicting or incorrect, this leads to problems on site with a consequent reduction in the quality of the work, delays and increased costs.*

[Building Project Information Committee (1987)].

Much of the research carried out by the author in this area has been published elsewhere [Moore (1996b,1996c); also appendix 1], therefore this chapter is largely a summary of those publications.

### 2.1 The Reason For Buildability: Lack Of Shared Knowledge.

The UK construction industry has sought to identify reasons why the construction product encounters problems in achieving client requirements Moore(1993a)]. In the early 1980's buildability was 'marketed' as one approach to overcoming the reason suggested for these problems occurring; a lack of shared knowledge between constructors and designers [Moore (1996a), (1996b)]. One example of this is Illingworth's (1984) conclusion that the British construction industry would only be able to equal the efficiency of its global competitors by studying, and acting upon, the requirements of buildability. Twelve years on from Illingworth's call, the lack of shared knowledge between designers and constructors is still being noted by researchers [Yamazaki (1992), Schaefer (1993)].

There is the possibility that lack of shared knowledge is a problem which has persisted throughout the history of the industry. The alternative suggestion is that, for whatever reason(s) the construction industry has introduced, in its

relatively recent past, forms of design and building organisation, and/or methods of production, which have brought this about [Moore (1996a)].

## **2.2 Historical aspect of shared knowledge.**

The problem of buildability is suggested as having its roots much further back in time than is indicated in the current literature, and there is evidence indicating that the evolution of the design profession has contributed towards the modern-day need to explicitly consider buildability [Moore (1996a)].

**2.2.1 Pre-medieval .** Design of the building product proceeded in an evolutionary manner for several thousand years, as materials were utilised on a trial and error basis. The ancient Egyptians, as one example, used the new material of stone in constructing columns following the manner of the reed bundles previously used for column construction [Young (1986)]. The only recorded significant attempt at formalising this evolutionary development was by the Roman writer Vitruvius in his *The Ten Books on Architecture* [Wilson (1979)]. Many of the principles cited by Vitruvius still apply to present day town planning and his work is recognised as the first recorded attempt to produce guidelines for building design [Young (1986)].

The *Ten Books* begin with a discussion on the education of the architect and include definitions of the terms 'practice' and 'theory' as used by Vitruvius [Morgan (1960)]. Practice can be seen as the equivalent to the building phase of modern-day construction, whilst Theory can be seen as the equivalent to the design work currently carried out by the architect. Vitruvius was of the opinion



that practice and theory would, ideally, be combined by the architect [Morgan (1960)]. This has been suggested as recognising the importance of knowledge regarding both the design and building processes to the achievement of a satisfactory product.

Architects of a more modern persuasion, however, have criticised Vitruvius as being someone from a practical background who had read a good deal and formed some theories about design [Allsopp (1962)]. Those design theories, moreover, possibly came from earlier Greek writers; he clearly valued Order, Arrangement, Eurythmy, Symmetry, Propriety and Economy. Several of these appear to have been developed from earlier Greek work [Morgan (1960)]. There can be no doubt that the majority of the important structural principles were certainly identified before 1000 B.C. [Allsopp (1962)].

Irrespective of the concerns regarding Practice and Theory, there was always the problem of communication between members of the construction team. An example being the construction of an aqueduct, planned by Nonius Datus, in the second century A.D. Part of the aqueduct had to pass through a mountain and two teams of contractors started tunnelling from each side of the mountain. Unfortunately, they missed each other. Datus returned to the site to check his specifications and found that they were correct but that the contractor had failed to follow them [Liversidge (1976)]. The fate of the contractors is not recorded.

**2.2.2 Early medieval: 400 A.D. - 1200 A.D.; Saxon and Norman.** During the Saxon period formal architecture in England was typified by Smith (1906) as

being of rude work and rough material. During this period English architecture continued developing in an evolutionary manner, with the system of organisation being basically one of verbal instructions and working out of design problems on the job [Allsopp (1962)]. There were, however, specific examples of advanced design, such as elements of the Priory church at Deerhurst [Dudley, Jackson, Fletcher (1961)]. Despite the gradual development of a more complex architecture, no evidence has been found in the literature to suggest any separation of the design and building processes during this period.

The Norman period saw a relative explosion in building work in England, with almost every important church being rebuilt and many new churches being founded. It was against this background that the great numbers of skilled and semi-skilled building workers who made later architectural developments possible were trained, particularly in masonry work [Allsopp (1962)]. The general characteristics of Norman building suggest that it is probable the Normans were concerned with designing buildings which were relatively easy to build. The early architecture could be argued to be achievement of buildability through an early form of standardisation [Moore (1996b)]. Detail work was certainly standardised [Allsopp (1962)], as the Normans generally appeared to require rapid, rather than grandiloquent, architecture. No evidence has been found in the literature that this was achieved through any split between the design and building processes.

The next significant developments in architectural conception took place in

Europe, with the initiatives of Gothic architecture in what Allsopp (1962) claims to be one of the greatest periods in the history of architecture. This greatness, however, should not be seen in terms of art, in that Gothic craftsmen did not consider their work, even on the grandest cathedrals, to be art, regarding themselves as masons or stonecutters rather than artists [Wilson (1979)].

### 2.2.3 *Late medieval: 1200 A.D. - 1550 A.D.; The Guilds and Masons.*

Increasing trade allowed members of the Merchant Guilds to amass sufficient wealth for them to consider exhibiting in the form of increasingly elaborate dwellings. In order to produce such dwellings, the Merchant Guilds set up craft guilds which in turn established the apprentice and craftsman system. Given the building technology and materials available at the time, the two most powerful trades represented within the guilds were the carpenter and the mason.

The term *Fre Maccons*, or Free Masons, was first used in 1396 to contrast the work of this highly skilled group with that of the lesser skilled *ligiers*, or layers, of stone. The medieval "architect" was frequently a master mason who was capable of drawing plans and design details for others to work from, and also carried out supervision of work in progress. At this stage of the development of the construction industry there was no significant divorce between the process of design and the process of building due to the stringent rules imposed on themselves by the Master Masons.

One consequence of the dignity bestowed upon the Master Masons and Master

Carpenters was that they can be credited with responsibility for beginning the task of organising the building industry [Melville, Gordon (1984)]. Such masons and carpenters were responsible for some huge sums of money, for hiring workmen and for site organisation [Knoop, Jones (1967)]. The industry continued to expand in response to demand from an increasingly large and wealthy middle class, but the conservatism of patrons meant that new technologies and materials were resisted until the late 16th. century, when the rate of building began to slow in some areas of the country, [Johnson (1991)] and the Renaissance arrived in Britain.

**2.2.4 The Renaissance Architect .** The Renaissance saw the introduction of new materials and technologies from mainland Europe, where the Renaissance had started sometime before reaching England, as well as a revival of the work of Vitruvius. The first Latin text of Vitruvius was published, with illustrations, in 1511 and the principles stated therein seem to have had a considerable impact upon architects of the period. This is most evident in the Italian churches of the early 16th century [Wittkower (1988)]. However, the previously noted concerns of Vitruvius regarding Practice and Theory do not seem to have been as important to Renaissance architects as were his design principles. An early example of this is the assertion by the Italian architect Alberti, in his *De re aedificatoria*, that the aesthetic appearance of a building consisted of only two elements: Beauty and Ornament [Wittkower (1988)]. Beauty was essentially a harmony inherent in the building which results from objective reasoning concerning such matters as proportion. Ornament was any act of embellishment of the building, even to the extent of considering the

candlesticks to be used in a building. It is at this stage that the first steps in the progressive separation of the design and building processes were taken by architects.

By the late 16th. century the French architect Philibert Delorme was able to write on his outspoken view that not all those who designed buildings were worthy of the title of architect. In Delorme's view patrons should employ architects instead of some master mason who, more often than not, had no better judgement than the patron himself [Wilkinson (1977)]. In effect the architect, in Delorme's terms, was becoming a practitioner of Liberal Art. This in itself represented a progression, and further development, of the earlier work by the Italian Alberti.

Alberti, in his treatise *Della pittura*, made it clear that the achievement of the architect was not a matter of manual skill, but an intellectual feat. The architect was seen by Alberti as an artist-intellectual whose activity had no connection with that of a craftsman. The divisions which appeared at this time between the liberal art of design and the mechanical art of construction eventually became so established as to be difficult to bridge in either direction [Wilkinson (1977)].

The first detailed description of an English architect's education in the Renaissance period relates to John Webb (1611-72), who trained in the office of Inigo Jones. Whilst serving his articles he was said to have been instructed in mathematics as well as architecture by Jones. There is no mention of instruction in the mechanical art of building, and as Webb's career developed

his visits to 'jobs' in progress were infrequent as he would send working drawings and details to his various clients, along with instructions as to how they were to be carried out [Briggs (1974)]. In such a manner the Renaissance saw the architect increasingly adopting a role which would be readily recognisable by the modern architect, and also estranged him further from the mechanical art of building.

*2.2.5 The Victorian architect.* Architects of the Victorian period predominantly arose from the middle classes, and there are no recorded instances of artisan's offspring rising to fame as had happened during the Renaissance. By the commencement of the Victorian period the enlightened gentleman-architect had become firmly established in England. The education of such architects relied heavily on the variable standards of the architectural pupillage system, along with occasional lectures at the Royal Academy and some foreign travel.

The training supplied to the articled pupil involved a twelve hour day dealing with surveying, measuring, costing, superintendence, and draughtsmanship. Many articled pupils supplemented their office training by sketching and measuring buildings on their Saturday afternoons off [Briggs (1974)]. This is somewhat surprising given that the Royal Academy Schools had, from their inception in 1768, supposedly offered the first formal architecture training in England. In general, the profession at this time continued to be more concerned with matters of business ethics and status than with education. RIBA membership represented only 9% of the profession by the mid 19th.

century [Barrington (1960)].

A number of architects expressed considerable resistance to the concept of a specialist profession. Ruskin, himself a RIBA member, expressed in an 1865 address to the RIBA the wish "...to see the profession of an architect united, not with that of the engineer, but of the sculptor." [Walton-Ely (1977)]. Ruskin was not alone in his opinion that architectural design was essentially the art of decorating structure.

Industrialisation of the construction component manufacturing processes had been increasing since the latter part of the 18th. century and had resulted in a number of innovations, particularly prefabricated modular skeletal structures, a famous example of which was the Crystal Palace of the 1851 Great Exhibition [Herbert (1978)]. These structures were largely engineering products and as such represented a challenge to the architectural profession of the time. The majority of the architectural profession responded to the challenge from engineering by withdrawing into revivals of those vernacular and craft traditions which the likes of Delorme and Alberti had so strongly sought to demote. The most successful example of this withdrawal was the Arts and Crafts Movement of William Morris and various colleagues.

By the turn of the century the RIBA still only represented 10% of the profession. The other 90% still clung to the Romantic ideal of artistic autonomy in combination with the belief that architectural design was representation of an imponderable body of skills. These skills were held to be as difficult to define

in a legal sense as they were unassessable by the compulsory examinations introduced by the RIBA in 1887. It is of relevance to examine the concept of the architect as both technician and artist in more detail at this point. Architects are possibly unique in that, whilst the general pattern of developing professionalism (see Figure 13) holds, the architect claims to be both a skilled technician and an artist, with the artistic temperament of architects being noted by Carr-Saunders and Wilson (1933). The architect's claim to both technical knowledge and artistic insight, with its implications for the relationship between architect and client, has dominated the development of the architecture profession [Barrington (1960)].

STAGE	CHARACTERISTICS
One	Foundation of a voluntary association, excluding unqualified or other persons likely to lower public esteem.
Two	Development of an explicit code of conduct.
Three	Growth of a system of tests and examinations
Four	Extension of control over the relevant educational institutions.
Five	Widening of interests from national to international level.
Six	A movement towards statutory registration.

Figure 13. General pattern in development of professionalism.  
[Summarised from: Barrington (1960)].

2.2.6 *Early 20th. century architects.* By 1900 some 15,000 architects were RIBA members, and architects found their autonomy in design reduced as architecture effectively became a closed profession for the first time. As operatives within the manufacturing industries moved towards greater and



greater specialisation, architects found themselves being asked to take on a new role: that of communicator between the specialists. An important aspect of the communicator's role is to appreciate that not all the information available at any one time is relevant to the task being progressed. Selection of information has to take place. A further aspect is that not all of the information which is relevant will automatically be understood by the recipient. Many architects, particularly in the early 1930's, failed to appreciate that the empirical experience built up over hundreds of years of tradition in a craft based industry was no longer fully relevant as the construction industry became more of a technology based industry. Only when this was appreciated did architectural research commence, some fifty years after research had been adopted by the social sciences and one hundred years after it had been adopted by the natural sciences [Strike (1991)].

*2.2.7 Contemporary.* From the early 1970's the range of materials and techniques available to the modern designer began to expand considerably over that which had been available previously. Consequently, buildings have increasingly more rigorous performance standards, resulting in the need for designers to adopt a more scientific approach to the design process than has been exhibited previously [Young (1986)]. Gothic designers, for example, achieved slim building sections by having a 'feel' for their materials. Sections would be slimmed down on successive buildings until one collapsed, at which point the designers realised that the limit had been reached for a particular material and technique [Wilson (1979)]. Whilst prototype testing to destruction may have been a drastic design method, it was effective in an evolutionary

sense. Modern designers, however, have the use of software to analyse the structural performance of a design, allowing the performance limits of a given material and/or technique to be determined without the drastic action of a building collapsing.

2.2.8 Design processes.

1. 5 STEP DESIGN PROCESS	2. RITTLE'S SUMMARY OF DESIGN PROCESS	3. G.T. MOORE'S DESIGN PROCESS	4. RIBA ARCHITECTURE SERVICES
Initiation Imbalance	Identify The Problem	Problem Identification	Inception
Preparation	Collect Information Analyse Information	Analysis Of User Needs Programming	Feasibility
Proposal Making	Creative Leap Work Out Solution	Design Synthesis	Outline Proposals Schematic Design Detail Design
Evaluation	Test Solution	Selecting From Alternatives	
Action	Communicate And Implement	Implementation	Production Information Bills of Quants. Tender Action Project Planning Operation On Site Completion Feedback

Figure 14. Views of Design Process. [Summarised from Chandler (1987)]

There are a number of ways in which the design process can be viewed and within each of them there lies a grammar; those rules or stages by which the

design is produced. Designers will tend towards the selection of a particular grammar which reflect their values. Figure 14 outlines four different design processes, each with their own grammar.

Looking at process four, which is possibly the most frequently used in that it is RIBA's recommended Plan of Work, the emphasis is greater on the later stages of the process. It has been argued [Chandler (1987)] that this emphasis may be a factor in the common practice of revising construction details, materials used etc, during the building phase of a project, as it is seen as being the 'right' point at which to carry out alterations.

STEP	CHARACTERISTICS
1. Recognise the inherent complexity of design	<ul style="list-style-type: none"><li>* Understand the technological content.</li><li>* Decide on level of technological innovation.</li><li>* Determine all the sources of the design.</li><li>* Buy in specialist design as appropriate.</li></ul>

Figure 15. Characteristics of recognising inherent complexity of design. [Summarised from Gray, Hughes, Bennett (1994)].

The author suggests that there is an increasing need for architects not just to see themselves as technicians with artistic insight, but also as managers; in particular managers of the design process, irrespective of which process is adopted. Gray, Hughes and Bennett (1994) suggest there are ten essential steps to successful management of the design process. With regard to this thesis, step one (see Figure 15) is suggested as being the most relevant, in that it stresses an ability on the part of the design manager to recognise both

technological content and innovation. Any deficiency of ability in this regard will fundamentally impair the achievement of good buildability and that, given the indications noted regarding the technician/artist dichotomy, the architect may well suffer from such an inability. The resultant lack of technical process knowledge, particularly regarding on-site production, is suggested as being a contribution to the modern-day need to actively encourage consideration of buildability prior to commencing construction.

**2.2.9 Contemporary Recognition of Buildability.** Various contemporary reports show evidence of recognising the need to consider buildability. The earliest such example was the Emmerson Report of 1962, which suggested the development of a new form of relationship between designers and constructors [Emmerson (1962)]. This was deemed essential if the advice required to execute modern forms of building was to be made available. The Banwell Report (1964) identified the need to involve the contractor in the design process, as part of the team, before the design was completed. Banwell suggested a number of changes to practices and procedures within the industry. Unfortunately the Ministry of Public Building and Works did not accept the only recommendation made in what is seen as being the most important chapter of Banwell (chapter 1) to bring about the necessary co-ordination. Consequently the matter of 'cohesion' in the industry has never satisfactorily been addressed, and the buildability problem persists.

## **2.3 Conclusions.**

There exists evidence of a concern regarding what is presently referred to as

buildability, at various points in the evolution of the construction industry. The work of Vitruvius contains the earliest recorded concern of this type, and the design process utilised by the Normans contains aspects which can be considered as inferring buildability through standardisation. However, the evidence regarding the manner of training the designer, in particular the fact that there was no significant separation of the design and building processes, does not suggest that buildability became an explicit cause for concern until the Renaissance. The extent of this concern was effectively constrained by the nature of the industry; a limited range of materials and techniques were available to the architect. Nonetheless, the separation of the designer and builder into two professions, which commenced at this time, contributed to a crisis of identity for architects during the Victorian period; was the architect a follower of the liberal art of design, or of the mechanical art of building?

- \* There is evidence to suggest that this crisis was only resolved in so much as the architectural profession adopted the unique position of claiming to be skilled in both technical knowledge and artistic insight.
- \* Consideration of the various approaches to the design process further suggests that artistic insight and technical knowledge are not necessarily manifest in the required balance. The RIBA plan of work is cited as a particular example.
- \* The architectural profession has brought itself to the situation where it is necessary to reduce the number of failures in the building industry and

also to improve the quality of built architecture through a clearer understanding of the significance of the historical evolution of construction [Strike (1991)]. A decision is required on whether architecture is to be the practising of technical knowledge or artistic insight with regard to the building process.

- \* A contribution to the decision making process may be possible through the development of a design aid which seeks to offers the design professional construction knowledge regarding on-site production.

Chapter three will examine contemporary buildability considerations in order to further test the possibility of overcoming the separation of design and construction knowledge through the use of the proposed automated design aid.

### 3. CONTEMPORARY BUILDABILITY CONSIDERATIONS.

*...prefabrication has proved disastrous as an example of how to industrialise building precisely because of its excessive concern with technique, and for all the use it is now, it would be better banned.*

[Kroll (1986)]

#### 3.1 Difficulties Regarding Buildability.

The buildability problem has two main components: how to define buildability; and how to measure the effect resulting from the degree of its consideration [Moore (1996a); Moore, Tunnicliffe (1995); also appendix 1]. Both components have proved difficult to resolve since examination of the industry's production problems began to be seriously examined in the early 1960's. The report by Emmerson (1962) suggested the development of a new form of relationship between designers and constructors in order to make available the advice required to execute modern forms of building. Of particular concern was the lack of cohesion between the architect and the builder which was seen as adversely affecting building operations efficiency. Emmerson's cohesion problem is basically the same as the buildability problem, in that it arises from the poor communication of knowledge between constructors and designers which can be traced back to the Renaissance.

Communication problems were examined further by the Tavistock Report [Higgin, Jessop (1963)], which recommended that, when preparing the brief, care be taken to ensure imbalance did not occur due to the architect/sponsor being tempted to "...maximise architectural magnificence.." at the expense of technological considerations. Somewhat reminiscent of the production problems caused by Alberti's strive for magnificence in the design for the

vaulting of the nave at S. Francesco in Rimini during the fifteenth century [Ettliger (1977)].

The Banwell Report (1964) particularly identified the need to involve the contractor in the design process, as part of the team, before the design was completed. Banwell suggested ways in which the communication problem (termed 'independence') could be overcome, particularly changes to practices and procedures within the industry. These changes were not implemented. Consequently the matters of 'independence' and 'cohesion' in the industry have never satisfactorily been addressed.

3.1.1 *Measurement of buildability.* The earliest contemporary attempt to quantify the effect of design on buildability [BRS (1970)], examined the operation of cranes on construction sites and concluded that: "*If the site, layout or type of construction is such that this crane operation is difficult, then the whole process will probably be difficult and uneconomic*". The report did not, however, go beyond this basic statement regarding the relationship between the factors of site layout, type of construction, and uneconomic construction processes.

A further attempt to determine the effects of design on the construction process was a report [RICS (1979)] which compared the UK and American construction industries. Particular emphasis was placed on their respective design and contract procedures. Two of the conclusions of this report are of particular relevance and are quoted here verbatim:



- i) *Speed of construction in the USA is achieved by different work practices from those in the UK. Many of these result from the willingness of US engineers and architects to accept alternative designs from the contractors and sub-contractors, aimed at simplifying the building construction.*
- ii) *Detail design cannot be divorced from construction without major time and cost penalties.*

No meaningful figures were quoted by the RICS report regarding the value of buildability. The problem of putting a value on buildability remained until Gray (1983) proposed percentage figures for the financial benefit of good buildability. Gray also proposed that buildability could be achieved through two approaches: standardisation and simplification. Unfortunately, neither term was fully defined by Gray, a situation for which the author offered a resolution [Moore, Tunnicliffe (1994a); also appendix 1]. Gray's figures were developed from previous work [Gray (1981)] analysing the preliminary element of building production costs. Whilst Gray's analysis is doubtless vulnerable to criticism some fifteen years on, it is the only example of an attempt at such analysis located within the literature. The author therefore suggests that Gray's figures be taken as indicative of potential savings in production costs from the achievement of good buildability, rather than definitive, as the provision of definitive figures is an objective which lies outside the scope of this thesis.

### 3.1.2 *Defining buildability.*

An example of the difficulties faced in resolving this problem is that during the CIRIA (1983) programme of research on buildability, the term 'buildability' was used frequently by contractors without any definition for the term having been

put forward. This was taken to imply that building clients were not being allowed to obtain value for money due to the separation of the design and construction functions. On the matter of 'value for money', the CIRIA report identified one potential benefit: *"Good buildability leads to major cost benefits for clients, designers and builders."* CIRIA also identified buildability as being relevant to the failure identified by others [Banwell, Emmerson, Tavistock; see 3.1 above] to communicate construction knowledge between the design team and the construction team.

Current definitions do not clearly indicate how buildability may be measured. There are suggestions within the literature that recognition of buildability can be learned through the structured development of production knowledge based expertise [Ferguson (1989)]. There are also suggestions that buildability will naturally arise through the adoption of prescribed technologies such as system building [Strike (1991)]. There are a number of problems regarding the measurement of buildability within both approaches, which will be dealt with in more detail in section 3.2. At this point it is most relevant to note that neither approach offers an objective basis for the measurement of buildability. This programme of research has initially responded to this situation by:

- a) placing the content of Illingworth's definition in a more specific context (see section 3.3)
- b) developing a paper-based model of a proposed automated design aid (ADA) which would assess a design for its level of buildability, based upon the definition at a), and produce an objective measure.

No existing design aids which can assess the difficulty inherent in the realisation of the construction product from a paper or CAD design have been identified within the literature by the author. On this basis the proposed design aid represents an addition to existing knowledge.

### **3.2 Three Approaches to Achieving Buildability.**

Within the literature three basic approaches to achieving buildability can be identified: standardisation; simplification; construction into design. Sections 3.2.1 and 3.2.2 represent a summary of work by the author on standardisation and simplification [Moore (1995, 1996a); Moore, Tunnicliffe (1994a); see appendix 1 and glossary of terms]

**3.2.1 *Standardisation approach to buildability*** . Standardisation, within the concept of buildability, has been suggested by the author as being a similar philosophy to Ferguson's (1989) variety reduction, within which the optimum would be one universal component from which all buildings could be constructed. Whilst Ferguson acknowledges that such an optimum cannot be achieved, he does suggest that it can be approached, and offers five tactics for this: conversion; handling; repetition; handling; dimensional co-ordination. Moore and Tunnicliffe (1994b) have suggested that there are two problems regarding the application of Ferguson's variety reduction strategy for buildability: the need to develop a high level of production technology expertise; its affinity with system building technologies.

The true development of expertise depends upon the repeated application of

the basic principles and a willingness to learn from the results of that application [Dreyfus, Dreyfus (1986); Benner (1989)]. An inevitable result of this is that development of expertise takes time and the practising of trial and error analysis during such a time scale is likely to prove expensive. Consequently, Ferguson's strategy lacks the immediacy required to advise on buildability at the early stages of building design.

The problem of affinity with system building technologies is one of imposed technological solutions. Lawson (1986) suggested that the reluctance on the part of designers, in general, to accept system building technologies is that they are seen as being wholly convergent, closed methods of solving the design problem through imposed technological solutions. Moore (1993b) has suggested that buildability in a form which can be seen to impose constraints on design creativity (ability to balance divergent and convergent thinking abilities appropriate to the situation [Lawson (1986)]) will not generally be accepted by a profession whose main advertisement is the buildings produced by its creative process. Others [Clement, Lecland (1994)] have argued that much of the creative process involves correction and adaption of initial attempts at design solutions. The nature of this creative process is important in that the proposed ADA has an identified requirement to aid creativity in the achieving of a design solution.

Within standardisation, the achievement of buildability becomes dependent upon the successful imposition of production technologies upon the design process, rather than allowing for design led selection of appropriate



not seek to impose any technological solutions on the design problem. Neither should it seek to remove complexity completely from the building design. What is intended is to identify complexity within a design, evaluate that complexity, and then allow the designer to reduce, remove or accept it. Should the designer wish to accept the existence of complexity in achieving a particular design solution he, or she, can do so whilst being aware that particular emphasis will have to be placed on the detail(s) in question during the on-site production of the building.

The above view of simplification differs somewhat from that resulting from Ferguson's (1989) approach to simplification, which is that uniqueness can be achieved by assembling similar components in a variety of ways. This is doubtless so, in that brickwork bonding, for example, allows considerable scope for uniqueness in the final product. However, such uniqueness will not automatically achieve the status of creativity, as Ferguson's agenda is still one of achieving variety reduction through the imposition of technological solutions, within a convergent framework, to design problems.

Ferguson's buildability strategy can be summarised by the placing of his buildability definition ( $m/c/sa$ , where  $m$  = materials,  $c$  = components, and  $sa$  = subassemblies [Ferguson (1989)]. within the context of the construction process. The key aspect of this summary is suggested as being the decreasing of divergence as the product nears completion, which has repercussions for both the achievement of creativity and quality [Moore (1990)]. The resulting argument is that decisions regarding both design

creativity and product quality must be taken in the early stages of the design process. In chapter 2 the RIBA process was noted as encouraging such decisions to be made in the last stages of the design process. The error of such an approach can be exhibited by a brief consideration of a strategy which can be argued to have buildability implications in its application to a project: value engineering.

Value engineering can trace its roots back to the late 1930's and General Electric's Central Purchasing department [Macedo (1978)]. By the time buildability was being explicitly considered, value engineering was well developed in America, and being used to identify value in construction designs through asking six basic questions as outlined in Figure 17.

<b>ORIENTATION</b>	<b>INFORMATION</b>	<b>SPECULATION</b>
what is to be studied?	what is it? -what does it do -what does it cost -what is it worth	what else will do the job?
<b>ANALYSIS</b>	<b>DEVELOPMENT</b>	<b>PRESENTATION</b>
what does that cost? -which is least expensive?	will it work? -will it meet requirements -what is need to implement	what is recommended?

Figure 17. Six phases of value analysis.  
[Summarised from Chandler (1989)]

During the late 1970's value engineering was being used to identify savings in relation to the degree of project definition at each of the main project phases. The relationship between project phase, definition and flexibility for change

which was identified at that time is illustrated in Figure 18.

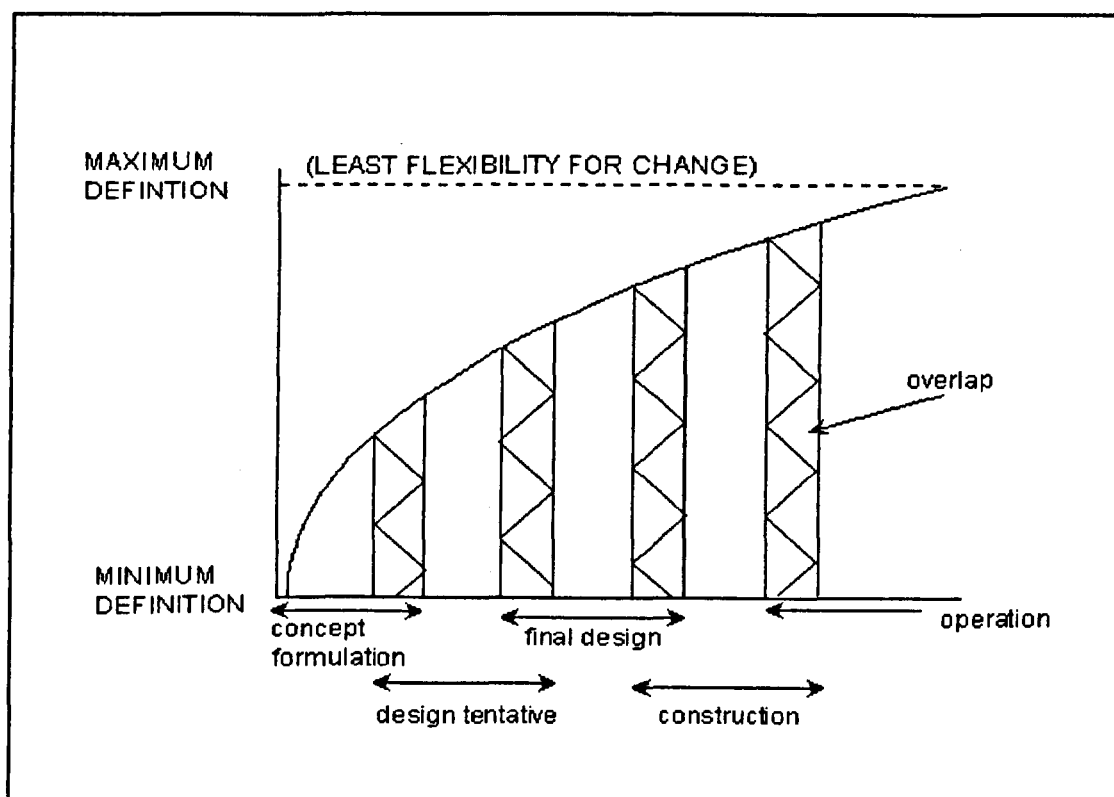


Figure 18. Project definition and flexibility.  
[Kelly, Male (1993)]

The key relationship is that between definition and flexibility at the briefing and sketch design stages: the greater the definition, the less the flexibility for change. On this basis, savings which could be classed as significant can only be achieved at the earliest design stages. Kelly and Male (1993) identified potential cost savings of 10 -15% from the application of a value management study during the briefing and sketch plans stages of a project. Likewise, any buildability approach can be expected to offer the most significant benefits by being applied at the early design stages. Ferguson (1989) anticipated savings of around 15% from the application of buildability during the design stage. Gray (1983) also noted that some 70% of total project costs are determined at



the completion of the early design phase, a figure supported by research in industries other than construction also. Kochan (1991) quotes Bernard Gonnet of Renault: *"At the beginning of a project, we get locked into a level of costs which is very difficult to change later on. If later on we find they are too high, it requires an enormous amount of time and effort to bring them down and the effects are only small."* A general relationship between design and project cost is suggested as being the first 30% of design development fixes 70% of the project costs [Leaney, Wittenburg. (1992)].

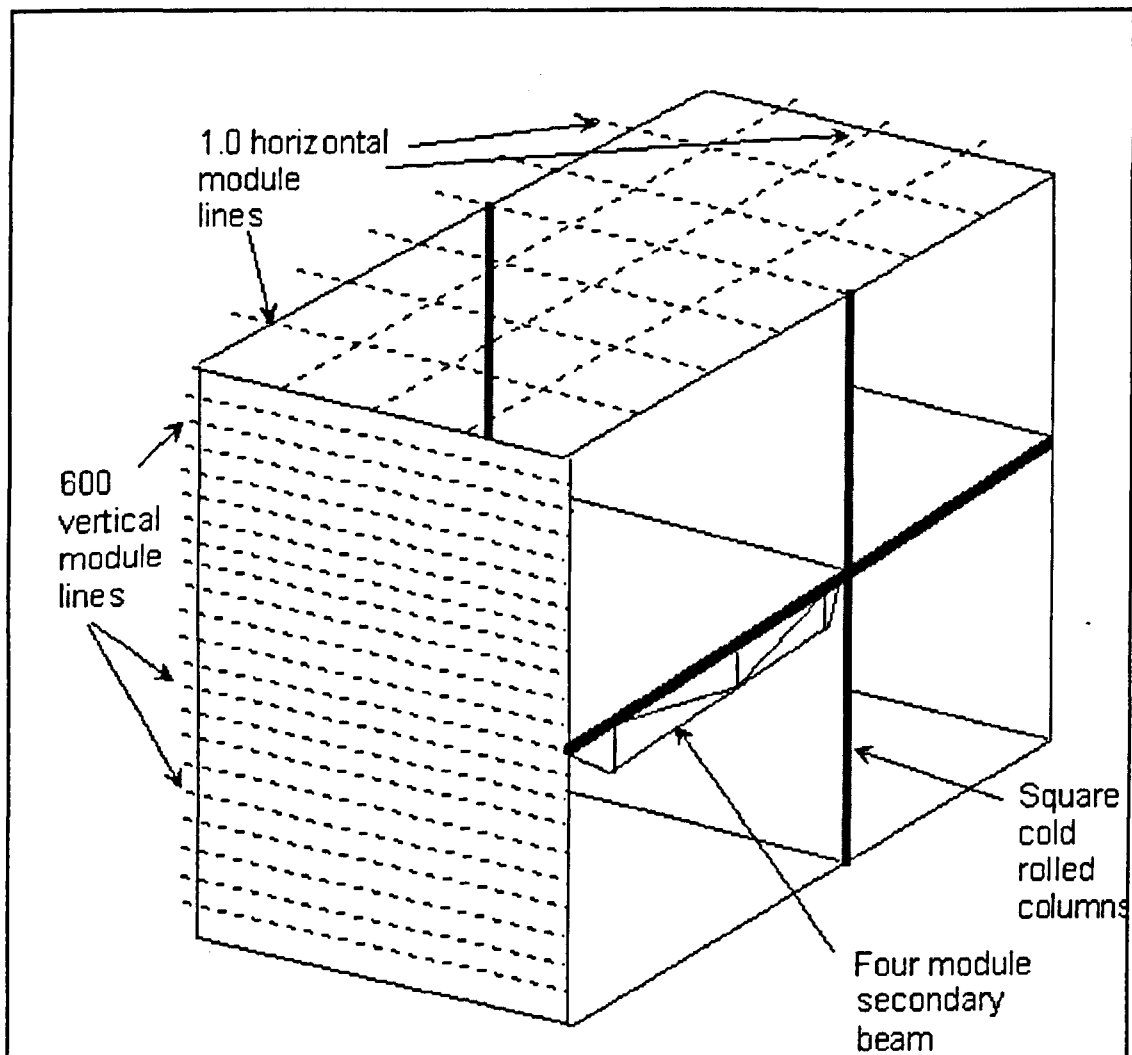


Figure 19. The open nature of CLASP.  
[Composite from Strike (1991) and Barry (1984)]

**3.2.3 Construction into design.** This approach does not emphasise either simplification or standardisation. Emphasis is placed on encouraging the design process to consider the possibilities of new construction technologies. As such standardisation and simplification may occur, almost by default, but are not the prime movers. An example of this approach can be found in the single standardisation approach to buildability which was generally accepted as a success: the CLASP system.

The pioneering Consortia of Local Authorities Special Programme (CLASP) was set up in 1957 on an initiative from Nottinghamshire County Council, who had developed their own standardised, prefabricated school building system. In 1958-59 31 schools were submitted for the programme, and the success of CLASP can be judged from the fact that by 1965 the number of projects submitted was 124 [Strike (1991)]. This level of success was achieved due to the system's open, or divergent, nature (see Figure 19) which was not typical of industrialised systems.

### **3.3 Lack Of Acceptance Of Buildability: The Role Of Quality Assurance.**

Buildability was not significantly adopted by the industry for various reasons. Moore and Tunnicliffe (1994a) suggested there has been an inconsistent approach to both defining and applying buildability which has resulted in buildability increasingly being replaced by Quality Assurance (QA), in its BS 5750 and subsequent ISO 9000 forms, as the claimed solution to production problems. BS 5750 would appear to have provided the industry with something never achieved by buildability; a structured system within which to work.

never achieved by buildability; a structured system within which to work. However, the BS 5750 system itself has been criticised by some as not being relevant to the construction process.

**3.3.1 *The Fall of Quality Assurance.*** The main criticisms of QA can be identified as relating to its manufacturing industry origins. It is possible to argue that QA is an administrative solution to a production problem. In this sense it can be viewed as an example of the standardisation [Moore, Tunnicliffe (1994a)] approach to buildability. This particular point is of importance in that standardisation does not relate purely to the technicalities of construction; it can also relate to forms of contractual and organisational relationships, and therefore could be expected to have a value with respect to the 'cohesion' problem. The extent of such a value does not appear to have been quantified in any detail within the literature.

Stanhope PLC claimed that BS 5750 actually reduced quality, and removed the compulsory compliance clause from their contracts. The replacement was a general requirement for an adequate "quality management scheme". Stanhope's concerns centred around the doubt that 5750 was flexible enough to help contractors produce better buildings [McLellan (1990a)]. A similar concern was expressed by Wimpey's quality assurance manager, John Ashford, who responded to Stanhope's actions by stating: "*BS 5750 is meant to ensure compliance with specification, it doesn't offer anything else.*" [McLellan (1990a)]. Moore (1993a) has suggested that there is no specification for good buildability.

A report produced for the British Standards Institution (BSI) in 1987 [McLellan (1990b)] was heavily critical of the relevance of BS 5750 to the construction process. This report has been withheld by BSI, but four of the ten characteristics of construction which were claimed to differ from those described in BS 5750 has become public. The four characteristics are summarised in Figure 20.

Figure 20. Summarised characteristics of construction industry which differ from BS5750. [McLellan (1990b)].

- 
1. One-off nature of construction in comparison to the repetitive nature of manufacturing.
  2. The difficulty of defining overall standards.
  3. Difficulty within BS5750 of dealing with the adversarial nature of construction.
  4. BS5750 starts in the wrong place. Quality management systems should not impose a set of predetermined working practices.
- 

Item four in Figure 20 was a consideration during the development of one of the alternatives put forward to BS 5750. The A007 module [McLellan (1990c)] was produced by the College of Estate Management in conjunction with The Polygon Group, and was intended as a guide to the application of total quality management (TQM) in professional consultancy firms within the construction industry.

A007 resulted from the claimed realisation that a quality system which is nothing more than a bolt-on to the process of production cannot work. When applied to knowledge based services (design can be seen as such a service)

this results in the need to recognise that training and a quality 'culture' are vital. Appendix 2 summarises the main points of A007.

### **3.4 Problem solving v. problem avoidance.**

The relationship between QA, buildability and the construction industry can be simplified to some extent by viewing it in terms of problem solving and problem avoidance. The author suggests that value engineering and the RIBA plan of work can be regarded as basically problem avoidance and problem solving, with regard to production, techniques respectively. This matter of problem avoidance/solving and quality in construction has been noted by Moore (1990), and is supported by the work of Burn (1990) regarding the effect on resource use of the two approaches as typified by the Japanese (problem avoidance) and US (problem solving) manufacturing industries.

The key point with regard to QA systems in general is that they have been insufficiently orientated towards problem avoidance within the specific requirements of the construction industry. The proposed ADA will seek to encourage a problem avoidance philosophy by aiding designers to identify possible production problems at the sketch design stage of the design process.

### **3.5 Design and Build: a buildability strategy to deal with independence?**

The first Design and Build (D&B) form of contract issued by the Joint Contracts Tribunal (JCT) appeared in 1981 [Ndekugri, Turner (1994)]. Over the following years the Chartered Institute of Building (CIOB) identified a number of advantages for the D&B approach to procurement; single responsibility, speed

of building, financial control, completion on time, economic building and client relationships [CIOB (1988)]. Buildability, resulting from the close collaboration between design and building teams resulting in the claimed elimination of unnecessarily complex detailing, was seen as being a contributing factor to completion on time. Only when considering speed of building does the CIOB supplement talk in terms of an integrated team of designers and builders, when the main benefits are claimed to be reduction of communication delays and overlapping of operations, the implication being that faster, rather than clearer, communication results. Such an interpretation may be justified by two recent concerns regarding the organisation of D&B procurement:

1. quality of building designs; resulting in talks taking place between leading architects and contractors, and the Construction Industry Council (CIC) with a view to developing a D&B code of practice [New Builder (1994)].
2. the increase in novated D&B contracts at the expense of 'pure' D&B (Alexander 1994). Pure D&B achieves its cost certainty at the expense of design quality, due to the organisation being contractor-led, whereas novated D&B passes design authority to external architects. Raul Curiel, of Architects Fitzroy Robinson, voiced concern over D&B's security of final cost by stating that "Contractors don't have the skills to cut costs through design" (Smit 1994).

Pure D&B suffers to some extent from a reverse form of the knowledge communication problem identified with 'traditional' forms of procurement. D&B clients are faced with the situation that contractors are independent of design process knowledge. It has been suggested that there is a requirement for further development of D&B procurement routes before the problem of independence can be truly said to be addressed, and D&B identified as a fully satisfactory buildability strategy [Moore (1996a)].

### 3.6 Continuation Of The 'Independence' Problem

Yamazaki (1992) noted that the construction system suffers in the lack of integration of basic knowledge about construction technologies between constructors and designers. There is a similarity between this problem and that noted by Emmerson (1962) over thirty years previously: "*...in no other industry is the responsibility for design so far removed from the responsibility for production.*" By seeking to overcome this lack of integration through the imposition of predetermined construction methods on the design process, previous buildability strategies have been inappropriate to the actual needs of the industry, and have therefore ensured their own failure. The buildability strategy proposed by this programme of research is therefore **not** about the technicalities of the construction process, but the management of information.

3.6.1 *Feedback Systems.* These can be seen as a variation on expert systems, and appear to have had some success in the US construction industry [Kartam (1996)]. These 'feedback tools' can be viewed as potential buildability tools, and are summarised in Figure 21. Two important points to note from Kartam's work are that:

1. lessons learned during the construction phase are not effectively incorporated into the design of other projects; constructors need to improve documentation related to, and communication of, buildability lessons learned.
2. the most effective feedback system is to bring experienced construction personnel on board in the earliest stages of the project to integrate buildability into the design and planning processes; design professionals often lack the practical construction knowledge required to make construction-driven decisions.

FEEDBACK SYSTEM	KEY FEATURES	ADVANTAGES	DISADVANTAGES
Architecture & Engineering Performance Information Centre (AEPIC)	Collates performance data on buildings from two sources: a major architecture /engineering liability insurance company; court case summaries involving building failures.	i) over 4,000 cases in data base. ii) 67 different data fields and numerous topics. iii) data catalogued from viewpoint of a forensic engineer. iv) many potential users.	i) no specific customer. ii) system lacks focus, resulting in no integration into actual practice. iii) use of third-party information means that filtering has taken place to protect the source of the information.
American Society of Civil Engineers (ASCE) <i>Journal of Performance of Constructed Facilities</i> .	ASCE committees have collected and categorised information on failures, accidents, and performance of hydraulic structures, such as dams, since 1987.	i) contains case study information related to specific structures and incidents.	i) narrowly focused on hydraulic structures. ii) suffers from the lack of a comprehensive classification system, which hinders communication of information.
Construction Industry Institute (CII) Constructability Task Force	Produces publications and packages of concepts related to improving the design/construction interface; <i>Constructability Concepts File</i> .	Generally seen as being highly useful in promoting constructability improvements and programs	i) not a true expert system.
US Army Corps of Engineers Construction Engineering Research Laboratory (CERL)	CERL has produced two systems; automated review management system (ARMS), and bidability, constructability and operability review (BCO)	ARMS: i) provides database management for comment manipulation and analysis. ii) aids in the constructability process. BCO: i) provides a tailored checklist based on the design stage. ii) contains over 2,500 comments.	ARMS: i) does not contain performance information. BCO: i) at prototype stage. ii) does not yet represent a complete design review package.
Naval Facilities Engineering Command (NAVFAC)	NAVFAC's most current system is a CLIPS (C language integrated production system) based review of CAD generated projects.	i) provides automated editing of comprehensive checklists to provide a customised checklist for a specific project.	i) provides constructability review comments, rather than a buildability assessment of the actual design being produced.

Figure 21. US construction industry 'feedback systems'.  
[Summarised from: Kartam (1996)].



Kartam notes that the most common formalised feedback system presently in use within the US construction industry is the postconstruction conference, the main function of which is to recap buildability lessons learned on-site so that mistakes do not re-occur. However, there are a number of problems with postconstruction conferences:

1. not everyone who may benefit is selected to attend.
2. many buildability lessons are forgotten by the conclusion of a project.
3. personnel are transferred to new projects, or are soliciting new work, so conferences may tend to be rushed through.
4. failure to document buildability lessons learned in a uniform manner which aids future retrieval. Such documentation as is produced is generally narrowly distributed.

[Kartam (1996)]

An interesting aspect of NAVFAC's current feedback system, with respect to the author's research, is its use of CAD layer naming conventions to extract information related to specific disciplines through the CLIPS inference engine. The author's proposed use of AutoCAD's layer naming convention in the assessment of buildability is discussed in chapter four.

### **3.7 The Latham Review**

The most relevant aspect of the Latham review with regard to this programme of research, was the target set by Latham of a 30% reduction in real (in relation to productivity) construction industry costs by 2000 [Construction Monitor (1995c)] for the UK industry in total. Eleven working groups were set up to deal with specific aspects of Latham's recommendations. These are summarised in Figure 22, with working group 11 being highlighted as the most relevant to this thesis.

Working Group	Aspect
One	Checklist guide on briefing
Two	Construction strategy code of practice
Three	Joint code of practice for the selection of subcontractors
Four	Quality/Price mechanism for consultant selection and the expansion of the Consultant's Register
Five	Single pre-qualification document for public sector work and expansion of the Contractor's Management Information System
Six	JAGNET and other training issues
Seven	Image of the industry
Eight	Equal opportunities
Nine	Education of construction professionals
Ten	Liability and Building Users insurance against Latent Defects
<b>Eleven</b>	<b>Achievement of a 30% reduction in real construction costs</b>

Figure 22. Review Implementation Forum working groups: 1994  
[Construction Monitor (1994)]

Working group 11 identified four priority areas, throughout which a common requirement noted was the need for the design and construction processes to work as one. Two specific recommendations by working group 11 are suggested as being particularly relevant to the proposed automated design aid:

1. the concept of true partnering should be encouraged. Savings can be made by the early involvement of all the parties in the design, specification and project structure.
2. with a large turnover of personnel in the industry, and the subsequent loss of personal knowledge, it is vital that guides are available which allow 'system knowledge' to be quickly communicated.

AREA	CAUSES	ACTIONS	IMPACT
A. Change	A4. Errors	Understand and eradicate the causes of errors.	M
	A10. Sequential activities	Establish blueprint of strategy to maximise parallel activity.	M
D. Waste & Duplication	D1. Too many layers	Streamline project structures through a 'Business Process Redesign' methodology. Foster team culture to eliminate bureaucracy and achieve common goals. Integrate risk management into planning process.	H
	D4. Lack of trust/ teamwork		H
	D11. Lack of risk management		M
E. Complexity	E1. On-site fabrication	Design standards to maximise off-site fabrication.	H
	E2. Lack of standardisation	Identify and publish benefits of standardisation.	H
	E4. Industry fragmentation	Establish common goals to achieve integration of industry.	H
	E8. Lack of buildability.	Improve buildability by early application of appropriate expertise/ methodology.	H
	E9. Inadequate use of integrated IT	Develop architecture for integrated IT system.	H
F. Conflict	F6. Adversarial contracts	Simplify contracts and remove 'adversarial culture'.	M
G. Timing/ Programme	G3. Understand the what and how before you start on site	Establish minimum standards of pre-planning.	M

Figure 23. Areas of avoidable cost pertinent to the proposed ADA.  
[Summarised from WG11 (1995)].

Working group 11 identified a number of common themes with regard to areas of avoidable cost, the causes of the avoidable cost, the actions required to eliminate those causes, and the level of impact on costs from taking that action.

The level of impact was classified as being one of; low (L), medium (M), or high (H). Figure 23 summarises the areas, causes, actions, and level of impact for each of the actions suggested by the author as being pertinent to the proposed ADA (automated design aid). Those items in the table which are boldened are suggested as being the most pertinent items. It can be seen from the table that those causes and actions identified within area E; Complexity, are all noted by working group 11 as having a high impact on avoidable cost. This suggests a recognition of the necessity to address the problems of complexity in design.

The author notes that the action proposed by working group 11 in response to lack of buildability; improve buildability by early application of appropriate expertise/ methodology, is consistent with the overall strategy proposed by the author and others [Moore (1995, 1996a/b); Moore, Tunnicliffe (1995)] for the proposed ADA.

### **3.8 Hypothesis**

The research carried out to this stage of the thesis has led to the development of a hypothesis, which states:

The production of a skill modelling based Automated Design Aid, to be used at CAD design stage, would allow task level buildability to be achieved through managing the transfer of appropriate knowledge from construction process knowledge workers to design process knowledge workers, ie simplification.

This hypothesis suggests there is only one main variable to be considered; the extent of the appropriate knowledge to be transferred between the two types

of knowledge worker.

### **3.9 Conclusions**

The overall conclusion of this chapter is that the problem of 'independence' within the industry persists. Previous attempts at solving this problem have been rooted in the technicalities of the construction process, and are therefore examples of imposing buildability through standardisation strategies. Such solutions have had little attraction to design professionals. Other specific conclusions are:

- \* The independence problem will persist until a creative design tolerant strategy for buildability is defined in terms which do not allow the imposition of unduly difficult designs on the contractor. Only then can buildings be constructed which add to the variety of the built environment, whilst allowing for an efficient process of construction. No buildability strategies presently exist which will achieve this.
- \* Buildability strategies can be categorised as either standardisation or simplification strategies. These are not seen as being mutually exclusive in principle, and it is possible for them to be used in conjunction.
- \* Value engineering principles indicate that buildability strategies are best implemented during the earliest design stages. The proposed design aid is intended for use at the sketch design stage of the design process.

- \* QA systems cannot be seen as appropriate solutions to either the 'independence' or buildability strategy problems. This is because QA only ensures conformance to a specification. No specifications exist for the reduction of 'independence', or the achieving of buildability.
- \* Design and build contracts are not seen as being effective buildability strategies, due to a variation of the independence problem, whereby contractors do not have sufficient design skills to cut costs through the use of design.
- \* Working Group 11 (WG11) of the Review Implementation Forum identified the cause of complexity in construction projects as including; industry fragmentation, lack of buildability, and inadequate use of integrated IT. The action proposed by WG 11 regarding buildability was to encourage the early use of appropriate expertise/methodology.

#### 4. INTENDED OPERATIONAL ENVIRONMENT FOR THE PROPOSED AUTOMATED DESIGN AID (ADA).

*For most applications, it is highly inconvenient for a user to work in raster-units or some other idiosyncratic, device dependent measure. Thus it is convenient to express coordinates in terms of any system of measurement that is convenient for the particular purpose at hand...*

[Mitchell (1977)]

##### 4.1 CAD Systems.

Modern CAD systems are currently being discussed within the UK construction industry in terms of fundamental concerns relating to the suitability of existing procedures for the procurement, design and constructing of new buildings [Day (1996), Latham (1994)]. Consequently, the role of CAD as both a technological and organisational force for change is increasingly being examined. Reviewing the history of CAD development presents an opportunity to identify previous attempts to improve the functionality of CAD systems. Given that the proposed automated design aid (ADA) is intended to operate within a CAD environment, such a review is relevant regarding the development of a prototype ADA.

**4.1.1 A brief history of CAD** The key developments in the history of CAD have been discussed by Moore (1996d), and the following represents a summary of that discussion.

Serious CAD development began in the early 1960's, with a significant early example being the Sketchpad system. Sketchpad ran on a TX-2 computer at MIT's Lincoln Laboratory [Sutherland, I. E., (1963)]. At this time IBM were also developing a CAD system; DAC-1 (Design Augmented by Computer). DAC-1 was released in 1964 for use in automobile design by General Motors [Prince,

M. D. (1971)]. Architecture, however, lagged behind engineering in the application of CAD systems, primarily because of the high cost of such systems. By the early 1970's decreasing equipment costs resulted in an increasing use of CAD systems in architecture, and CAD systems in general were moving from being used for 'numeric' operations, such as cost estimation and structural analysis, to more recognisably architectural design operations through the development of interactive graphics [Negroponte, N. (1973)].

SYSTEM	SPONSOR/DEVELOPER	INTENDED USE
CEDAR	Originally Post Office, redeveloped for later use by PSA	Originally design of Post Office buildings using SEAC system. Later use for PSA rationalised office building method
HARNESS	DHSS/Applied Research	In HARNESS hospital building programme.
OXSYS	Oxford Area Health Board/Applied Research	Oxford method of building
CARBS	Clwyd County Council/ Liverpool University CAD Centre	Computer Aided Rationalised Building System

Figure 24. System building related CAD packages [Mitchell, W. J. (1977)]

CAD development in Britain was tied to the various industrialised component building systems. One early example was the system developed by Newman (1966), which was a more sophisticated interactive graphics package than Sketchpad, and was used for planning the assembly of industrialised components into buildings. Such an approach could be considered an early attempt at buildability through standardisation, in which the buildability aspect



was implicit, rather than explicit. By the early 1970's there were a number of similar systems under development, all of which were linked to public-sector system building schemes. These are summarised as Figure 24. There is perhaps a link between this process of tying CAD development to system building, as a convergent design solution, and the level of acceptance achieved by buildability in Britain [Moore (1996a)].

An example of the difficulties experienced in the context of convergent design solutions can be found in the OXSYS building system CAD package. OXSYS was a component based technology used by Oxford Regional Health Authority during the 1970's. The OXSYS CAD package provided a central database of project information which was accessible through the automatic generation of drawings and schedules. This approach was found to provide cost savings of 10-15% when used at the sketch design stage by the design team to try out a greater range of design solutions than was possible without the system. However, those design solutions were constrained to the possibilities allowed by OXSYS components, such as only a strictly orthogonal design geometry being possible [Richens (1978)].

One CAD package not tied to component building technology was the Scottish Special Housing Association's House Design system, which was developed at the University of Edinburgh between 1969 and 1976 for use in producing project information concerning two-storey terraced houses of traditional brick, no-fines concrete, or timber construction. This package still suffered from the restrictions of purely orthogonal geometry and the need to impose a 100mm

and 300mm modular discipline on the design [Bijl, Shawcross (1975)].

The Royal Institute of British Architects (RIBA) survey of 1989 found that;

1. 25% of all practices used some form of CAD application.
2. 66% of medium to large (employing more than 11 architects) practices made use of 2D.
3. 50% of medium to large practices made use of 3D.

[RIBA (1990)]

These figures are supported by a recent CICA survey, which found that over 90% of large architectural practices in the UK use CAD systems, predominantly for 2D draughting work [CICA (1993)].

4.1.2 *Manner of CAD use: large architectural practices.* Winch and Deeth (1994) identified two main approaches to the use of CAD in twenty large (turnover of £3m+ and more than fifty architects) architectural practices;

1. presentations to clients at sketch and briefing stages in form of 2D, 3D, walk-throughs, fly-pasts and animations. Eighteen practices used CAD in this way.
2. during drawing production phase, typically down to 1:100 general arrangement drawings.

A third, lesser, approach was to use CAD in the production of detailed design drawings. However, only three practices used CAD to produce drawings at 1:20 or below. The primary reason being the expense of producing what are effectively one-off details using a CAD system. This expense was offset to some extent by the practices making use of the database facilities within their CAD systems to carry elements from one project to another. New CAD users

however, have been found to be taking advantage of the improved situation regarding PCs (increased power), which have become the preferred platform for users making extensive use of 2D draughting packages [Day (1996)].

Two differing approaches to organising company structure for the use of CAD have been identified [Winch, Deeth (1994)]. Using McCloughlin's (1989) typology these two approaches can be identified as centralised/dedicated and decentralised/non-dedicated. The former operated as CAD Bureaux, run and managed by architectural technicians, whilst the latter operated as Networked offices, managed and used by architects. Five of the surveyed practices ran as Bureaux and thirteen ran as networked offices. One advantage identified for the networked office is that it gives the Project Team control over, and responsibility for, the CAD resource, resulting in the divide between operator and designer being reduced. CAD use then becomes perceived as a normal part of the architectural design process.

Given the above it is suggested that an ADA of the type proposed by this research must target the type 1 user (presentations to clients at sketch and briefing stages in form of 2D, 3D, walk-throughs, fly-pasts and animations) and seek to operate at the sketch and briefing stages of design production, within a networked office type of practice. An ADA which operates at the sketch and briefing stages would also be consistent with the 30:70 design/product costs relationship previously discussed in chapter three. The main implication of this decision is the relative lack of detail concerning the design solution at the sketch stage.

**4.1.3 CAD platforms** Within large practices workstations and mini-computers predominate. However, the predominant CAD package is AutoCAD running on PCs, which is predominantly used as a second system. AutoCAD on independent PCs is generally judged to have insufficient capacity for the more complex projects [Winch, Deeth (1994)]. Given that the proposed ADA is intended to operate during the early design stages, the complexity problem will not occur, and PC based AutoCAD systems should not be excluded for this reason. Furthermore, the affects of increased computing power from hardware developments, such as the Pentium chip, would not have been discernible at the time of Winch and Deeth's survey. The proposed ADA will not be disadvantaged by adopting AutoCAD, running on a PC, as its environment.

**4.1.4 Review of CAD systems** A review of CAD systems was carried out to identify any system containing a facility for the assessment of task difficulty and/or buildability (see appendix 3). None were identified, but a general trend towards increasing the versatility of CAD systems was noted, an example being the engineering data model (EDM) [Eastman, Chase, Assal (1993)]. This seeks to provide a strategy for dealing with the diversity of information inherent in the production of a modern building through representing design knowledge about the building as an engineering data model (EDM). The EDM sets a standard for the integration of presently existing performance information about materials, components, etc. (eg. noise transmission data on composite floors), with information which may be produced at some point in the future by specialist suppliers (eg. design details for the connection between floors and steel frame members). The complex nature in which information modules are overlapped

within EDM, and the 'specification' nature of the system effectively preclude development of EDM to provide an ADA based on a simplification oriented buildability strategy [Moore (1996d)].

One CAD development which suggests further advances are possible is the 'Brick Dimensioner' package. This works seamlessly within AutoCAD AEC [CAD User (1993)] and represents an ADA which reduces the workload of the designer, whilst imparting some level of construction knowledge, regarding brick bonding and the use of standard special bricks, to the designer. The reduction in workload results from eliminating the need for the designer to refer to standard, AEC supplied brick tables. Constant reference to these tables can be both time consuming and a factor in reduced productivity. Brick Dimensioner's use of 'ghost' bricks provides an automatic check that wall lengths are multiples of brick dimensions. In this way, walls can only be drawn to whole or half brick dimensions with the result that walls of awkward dimensions are not designed into the project to cause later problems. In this manner the designer will become aware of the possibilities and constraints of brickwork bonding principles, rather than of AutoCAD's standard brick tables, which become redundant.

A further consideration of relevance at this point is the effect of the use of computers in general on the fragmentation previously noted as existing in the industry. Day (1996) identified two specific trends to the use of computers; integrating and fragmenting. Integrating use tended to utilise a main computer as a central database which could be accessed by professional groups. In the

main this integration remained confined to the design phase of a development, but speculative housing was noted as one area of activity where the integration was continued into the construction phase [Macneil (1994)]. Day concluded that the majority of computers were being used as islands of automation in a manner which reinforced pre-existing fragmentation, particularly the contractual separation between the design and construction activities. The legal and financial complexities resulting from any attempt to create an optimal flow of digital information from the designer to the constructor was seen as being a disincentive to integration. The proposed ADA seeks to operate in a manner which circumvents such problems.

**4.1.5 Layering conventions** From the late 1970's a number of possible approaches to describing the topology and geometry of a building were developed, and can be categorised as follows: regular grids/lattices; variably-dimensioned grids and lattices; polygon/polyhedron representations; dual-graph representations; smith diagrams; 3D graph-theoretic representations [Mitchell (1977)]. Geometric types and a summary of their main characteristics are listed in Figure 25.

By the early 1990's the range of categories had been reduced to three: wire-frame, surface, and solid geometric modelling [Kempen, Kok, Wagter (1992)]. However, in order to support design work in CAD systems, and to maintain quality in the design process, a system for controlling the data generated as the design proceeded was required. Layering of data within CAD systems was suggested as a solution to this problem, with the British Standards Institute

issuing BS 1192 Part 5 "CAD Layering in the Construction Industry" for public comment in 1989. In order to allow for efficient transfer of CAD drawings and their related data a convention for naming individual layers was developed by AutoCAD producers Autodesk.

GEOMETRIC TYPE	SUMMARY OF MAIN CHARACTERISTICS
Element	Possible bases are: 1. physical components; columns, walls 2. bounding surfaces; walls, floors 3. bounding lines; edges, intersections 4. enclosed volumes; rooms 5. abstract modules; squares, cubes
Attribute	Possible bases are: 1. primary geometric; width 2. shape properties 3. secondary geometric; volume 4. non-geometric; weight, U-value
Relations	Possible bases are: 1. adjacency data; element(s) adjacent to any given element 2. separation; distance between element(s) 3. alignment, symmetry 4. visibility; view of one element from another
Level of Detail	General progression in level of detail must be appropriate to the relevant stage of the design process
Assumptions	Description efficiencies can be achieved if general geometric assumptions are made, such as all angles being 90°. Data structures commonly used for storing geometric building descriptions cause problems in determining symmetry about an axis. Such structures would be unsuitable for use in design analysis or synthesis involving symmetry criteria. However, developing a building design outside of a framework of disciplined geometry also results in description and construction problems.

Figure 25. Building topology and geometry descriptions  
[Summarised From Mitchell (1977)]

FIELD	EXPRESSING	CHARACTER	MEANING
1	DISCIPLINE	A	architecture
2	CATEGORY	210	external wall
3	GRAPHICS	H	hatching
4	GRADE	1	thin pen
5	LEVEL	01	level one
6	STATUS	N	new
7	SCALE	D	detail
8	TIME	1	phase one

Figure 26 Autodesk layer naming convention: example use [Autodesk (1993)]

An example operation of the layer naming convention is illustrated in Figure 26. In this example a layer is identified as A 210 H 1 01 N D 1. This particular example is not exhaustive of the data concerning a given layer which can be defined by the user. Autodesk have identified at least four reasons for the existence of layer naming conventions:

- 1. to rationalise information transfer
  - 2. to create a common user environment
  - 3. to give users guidance in structuring their drawing file
  - 4. to provide a structure for quality control over a user's drawings
- [Autodesk (1993)]

The first of these reasons; rationalising information transfer, is suggested as being most relevant. Whilst considering information transfer it should be noted that data exchange standards have now become more universal (IGES - STEP now standard for exchanging CAD data and models), resulting in relatively straightforward exchanging of data between computer systems. It is now possible to create, render and animate relatively complex 3D models on PCs [Day (1996)].



## 4.2 Explicit and Implied Information.

The information held within a CAD file of a given design can be viewed as being either of two types; explicit or implied. This viewpoint is suggested as being a potentially valuable means of extracting (implied) data which lies beyond that which is obvious, or explicit. The building descriptions summarised in Figure 25 provide examples of explicit information; separation, distance between element(s), alignment, symmetry, and visibility. The various relations are briefly discussed below in terms of two generic categories suggested by the author; separators/occupants and adjacency. These may prove relevant to the operation of the proposed ADA as a means of assessing task difficulty. There is also a brief introduction to a third category which may be of relevance to both separator/occupants and adjacency; tolerances.

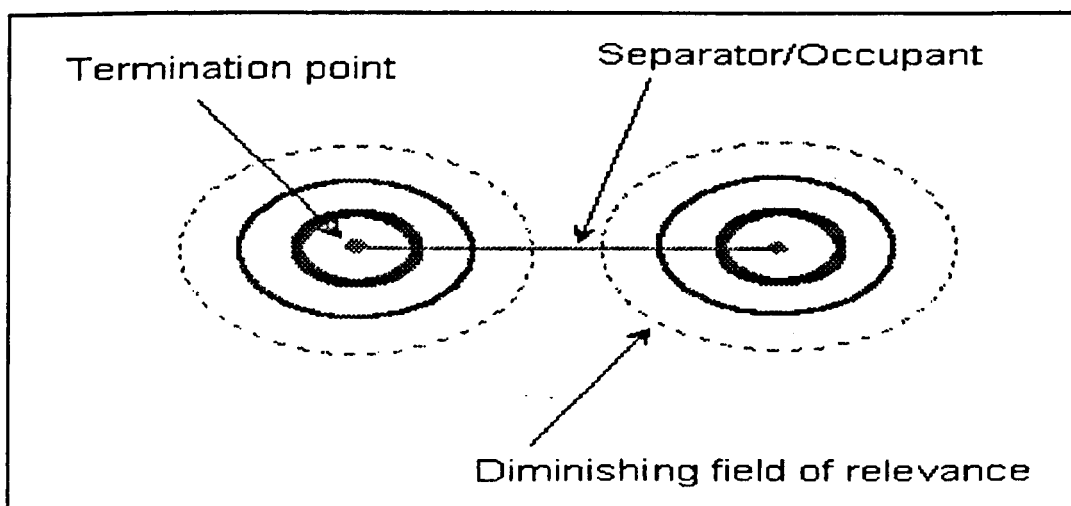


Figure 27. Suggested operation of 'field of relevance'

**4.2.1 Separators and occupants.** A line can be deemed to be performing one of two functions; it is either defining a distance which separates two points, or it is defining a feature which is an occupant between two points. It is

suggested that the respective psychologies of the design and building processes may have an effect with regard to perception of a given design drawing in terms of separators and occupants. The investigation of such an effect lies largely outside the scope of this thesis, with the exception of a possible relevance to the operation of skill modelling. This possibility is further examined in chapter seven of this thesis.

**4.2.2 Adjacency.** Moore (1996d) has suggested that there exists a diminishing 'field of relevance' around the termination points of a given line. Figure 27 illustrates one interpretation for fields of relevance. Any additional separators or occupants which occur within such a field of relevance may prove to be relevant to the interpretation of the original line. This was recognised by Mitchell (1977) in his discussion of building topology and geometric descriptions, through the use of the geometric type 'relations'; a possible base being adjacency data (see Figure 25). Separators or occupants laying towards the periphery of the field may have less interpretative relevance than those laying close to the centre of the field. This argument is reflected to some extent by CAD system configuration variables such as AutoCAD's APERTURE variable. This variable allows the user to set the target height at which the system will 'snap' onto an object placed in the current workspace [Autodesk (1992)]. By setting APERTURE to a low level, objects have to be placed closer to the existing artefact with which they are to be linked, than would be the case with APERTURE set at a high level.

**4.2.3 Tolerances.** The level of interpretative relevance of a given

separator or occupant may prove to be variable with regard to the tolerance applicable to it. Tolerances may prove to be a significant factor in the rate at which fields of relevance diminish around individual terminations. Such information is highly unlikely to be explicit at the 30% stage of design development unless the interactions of the components being utilised are known from previous experience (the advantages of system building technologies in this respect were discussed previously).

Furthermore, it is argued that design technologies can impact on the effectiveness of the design process. The extent of this is (somewhat light-heartedly) epitomised by the so-called First Law of Data Dynamics [Richens (1994)]; CAD system intelligence is inversely proportional to flexibility. Additionally, work carried out on the Intelligent Computer Assisted Design System (ICADS) has identified problems in 'adding' intelligence to present CAD systems [Pohl, Myers (1994)]. The main problems include; information-poor geometric descriptions of artifacts, difficulty linking reasoning agents to resource demanding CAD systems, and the lack of an existing cooperative model allowing interacting multiple agents within a CAD environment.

An example of the problems involved in the adding of intelligence to CAD systems is the work carried out by Radford and Mitchell (1986) on an experimental system which automatically generated eaves details. The system utilised an expert system linked to a CAD package. The system has not as yet progressed beyond being able to generate eaves details suitable for Australian domestic dwellings between the years 1910-1912. The value of the expert

system approach to increasing CAD system versatility with regard to buildability assessment is discussed further in chapter six.

### 4.3 The Proposed Role of Attributes.

In processing CAD file data, the proposed ADA can be seen effectively as searching the data for members of a domain. This domain is referred to by the author as buildability attributes. The author proposes that the prototype ADA will utilise only one attribute (tolerance requirements), thereby simplifying development and testing with regard to the supporting theory. However, it may be of general benefit to consider the properties suggested as being within the domain of each of the attributes identified thus far. These properties are intended to focus, as far as possible at this stage of development, in an objective manner on the data which could be extracted from CAD file layers (see 'layer naming conventions').

ATTRIBUTE	PROPERTIES
1. Tolerance Requirements	Spatial rules governing completion of each high level task (HLT) eg. bricklaying.
2. Range	Number of different HLT / Times each occurs
3. Interfacing	Fixing requirements at each change of HLT
4. Sequence	Order in which HLT are to be carried out / Installation precedence
5. Access	Space available to HLT / Space required by HLT
6. Closed insertion	Installation precedence

Figure 28. Suggested properties of individual buildability attributes.

Figure 28 lists those attributes, and their associated properties (the role of high level tasks is discussed further in chapter six), suggested by the author as being relevant to this programme of research. These attributes are seen as being explicit within the CAD file; attributes can only be determined within the data resident in a CAD file by the application of relevant knowledge regarding production requirements. In order to achieve this the ADA will have to construct some buildability knowledge for itself. This will require the rules driving the ADA to be structured in such a manner as to cause it to search the CAD file layers for data which can be viewed in terms of buildability attributes such as tolerance requirements.

Detailed discussion regarding the development of the full range of attributes and properties will not be entered into within this thesis. However, Figure 29 illustrates a possible link between Ferguson's (1989) hierarchy of buildability and the author's suggested buildability attributes for use by the proposed ADA. Whilst Ferguson's work on buildability contains good exemplars for each grade within his hierarchy, those principles which guide the process of assessing designs into hierarchy grades are not readily accessible. The link suggested in Figure 29 attempts to provide an explicit basis of assessment for each grade, whilst also allowing the manner in which CAD file data is processed by the ADA to be checked by reference to Ferguson's hierarchy. This would be particularly helpful as an early check during the development of the full complement of suggested attributes; a task which the author suggests as representing further research.

FERGUSON'S HIERARCHY	MOORE'S SUGGESTED BUILDABILITY ATTRIBUTES
1. Assembly impossible	Closed insertion / Tolerance Requirements / Sequence / Access / Interfacing / Range
2. Assembly only possible with extreme difficulty	Sequence / Access / Tolerance Requirements / Interfacing /Range
3. Assembly possible but difficult	Tolerance Requirements / Interfacing / Access / Range
4. Assembly straight forward but perverse	Range / Interfacing / Tolerance Requirements
5. Assembly easy	Tolerance Requirements

Figure 29. A possible relationship between Ferguson's hierarchy (summarised from Ferguson [1989]) and Moore's buildability attributes.

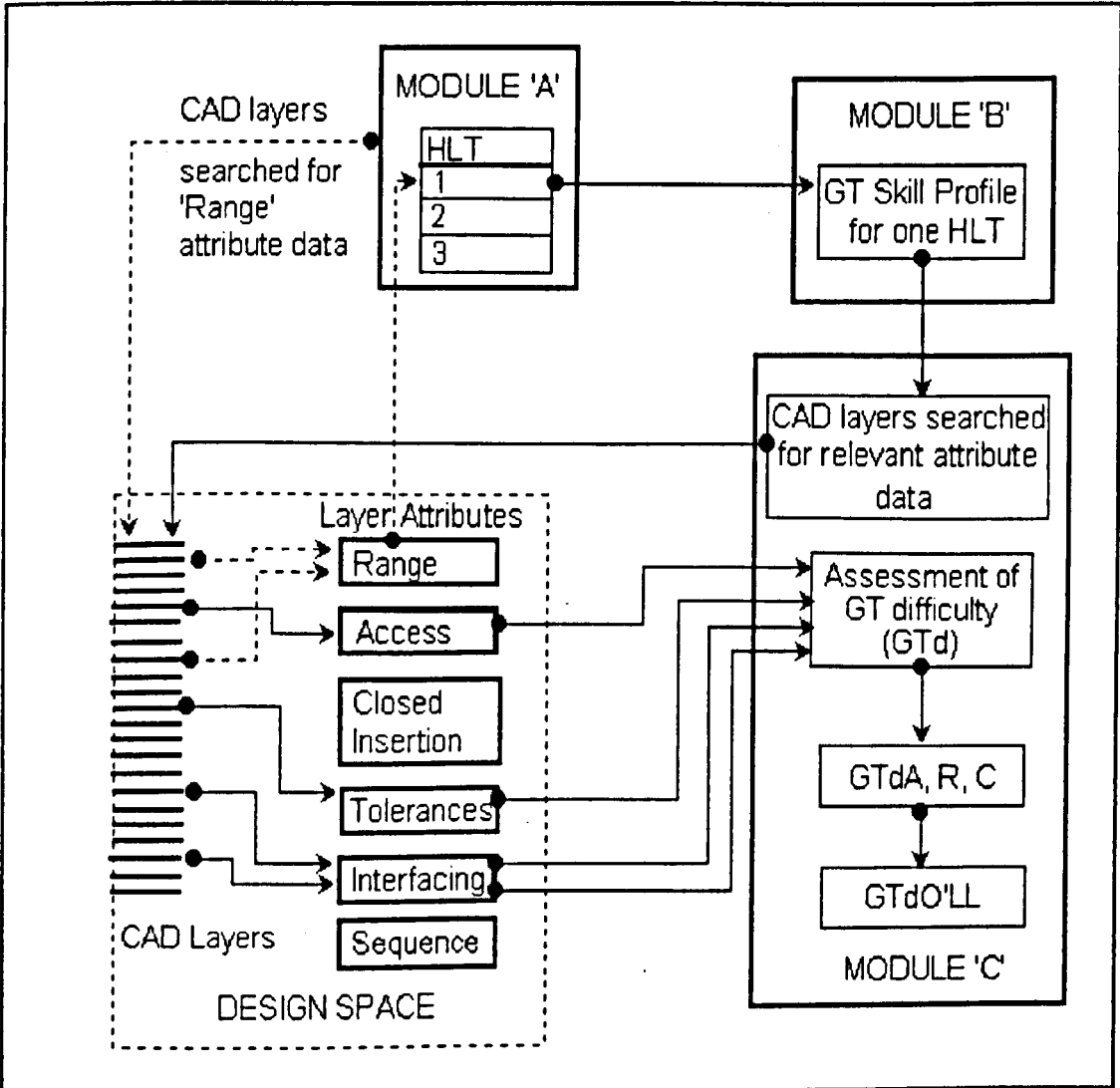


Figure 30. Suggested functionality of modules 'A', 'B' and 'C' with regard to CAD layer attributes

Figure 30 illustrates the proposed ADA's modules interrogating CAD file data. In this hypothetical example module 'C' identifies only two attributes which have any impact upon buildability assessment; 'range', and 'interfacing'. Reference to Figure 29 shows that the presence of these two attributes would indicate a level of buildability on Ferguson's hierarchy approaching 4 (Assembly straight forward but perverse). The ADA could therefore be expected to produce a buildability assessment indicative of a reasonably easy to build design. Such an assessment could only be taken as being indicative, as the prototype ADA's functionality aims for comparison of different versions of a design solution to each other, rather than the rating of a design's buildability on any scale of absolutes. The role of generic tasks (GT) indicated in Figure 30 is discussed further in chapter six.

Subject to the matter of attributes proving to be of relevance to the buildability assessment problem, the author would anticipate it to be a suitable area for further research outside this thesis (see chapter eleven). For the purposes of testing the theory regarding attributes, it is proposed to develop only one attribute in further detail.

#### **4.4 Information Transfer**

Adoption of AutoCAD as the working environment for the proposed ADA reduces the problems of the ADA reading information from a range of CAD packages. This programme of research will only consider the reading of data from AutoCAD utilising the layer naming convention discussed previously. Future development of the proposed ADA outside this thesis may wish to

examine methods by which files from packages other than AutoCAD may be processed by the ADA.

AutoCAD have supplied a file format to enable customised packages to read AutoCAD drawing files. This is the Drawing Interchange file format known as DXF, which can be read by all implementations of AutoCAD. In addition to DXF, AutoCAD also supports the Initial Graphics Exchange Specification (IGES). AutoCAD drawing files can be written out in IGES format and IGES files can be read and converted to AutoCAD's internal format.

There is a further file type available within AutoCAD, referred to as Binary Drawing Interchange (DXB), which allows exchange of geometric data for use in extreme functions such as rendering [Autodesk (1992)]. The author does not, at this point, envisage the operational requirements of the proposed ADA to include such data, but cannot absolutely rule out the possible need to utilise DXB files. Given this situation, it would appear to be prudent to orientate the proposed ADA towards the use of DXF/DXB files, rather than IGES files.

DXF/DXB files have a further advantage in that they are standard ASCII text files and as such can be read by other specialised programs for further analysis. This allows the possibility of developing the software version of the proposed ADA using a programming language other than AutoLisp (the development language for AutoCAD), such as Visual Basic.



#### **4.5 Conclusions.**

A number of clear conclusions can be stated about the work carried out during this stage of the research programme.

- \* The historical development of CAD systems has seen a change of emphasis away from generation of production information to the increased use of 2D draughting, and more complex 3D presentations of the building. An increasing trend towards greater versatility of CAD packages has also been noted.
- \* A preferred point of use has been identified for the proposed ADA; at the sketch / briefing stage of design. The main implication of this decision is the relative lack of detail concerning the design solution at the sketch stage.
- \* A target group of CAD users has been identified; type 1 users (presentations to clients at sketch and briefing stages in form of 2D, 3D, walk-throughs, fly-pasts and animations).
- \* No existing CAD 'add-ons' have been identified as being currently capable of assessing a design for buildability.
- \* AutoCAD has been adopted as the prototype ADA's environment, and DXF/DXB files have been identified as a possible basis for the interchange of data between AutoCAD and the ADA.

- \* The scale of drawings representing the data to be analyzed by the ADA will be 1:100 or greater.
- \* Problems of adding intelligence to CAD systems relate to; information poor nature of artifacts; difficulty linking reasoning agents to resource demanding CAD systems; lack of co-operative model allowing interacting multiple agents within a CAD environment, have been noted.
- \* Factors for further investigation have been identified as explicit and implied data related designs produced in a CAD environment. The role of separators/occupants, adjacency, and tolerance requirements have been particularly noted as possibly being relevant to the operation of the proposed ADA in conjunction with a CAD system. Tolerance requirements have been selected for further investigation

The strategy proposed by this programme of research, buildability through simplification, is not rooted in the technicalities of the construction process, and is not tied to specific technologies such as system building. By emphasising the management of information, the proposed Automated Design Aid would take a radically different approach to buildability than any previous buildability strategy.

This research proposes an automated design aid which acknowledges, and seeks to work within, the capabilities of a presently existing CAD system (AutoCAD), whilst providing the designer with useful decision support regarding

design corrections and adaptations to improve buildability. The functionality of such a design aid is discussed further in chapter six.

## **5. EXISTING APPROACHES TO ASSESSMENT OF TASK DIFFICULTY, AND DEFINITIONS OF OPERATIVE SKILL**

*So how exactly is this instant assessment of the rate of working of an operator while he is actually working made? This is a difficult question with no precise answer.*

[Jay (1981)]

The research carried out during the initial development of an assessment model covered several areas in order to identify structured objective systems for the assessment of task difficulty. This research was not constrained to the construction industry; manufacturing industries were found to be using well developed, but highly specialised assessment systems. Information was particularly sought on systems linking levels of operative skill and the assessment of task difficulty.

### **5.1 Work Study and Ergonomics**

Moore (1996a) has discussed these areas in the context of a possible contribution to the automated assessment of buildability (see also; Moore, Tunnicliffe (1995a), appendix 1). The following represents a summary of that discussion.

Work study has two main sections; method study and work measurement. A related area of study is that of ergonomics (the fitting of the task to the person) [Pulat (1992)]. Within the study of ergonomics, a similar philosophy to that proposed by the author for the automated design aid (ADA) is exhibited in the area of human integrated design (HID) [Longmate, Welker (1985)]. HID systems work within human capabilities and limitations [Pulat (1992)]. Figure

31 illustrates the general operation of HID.

The design aid proposed within this thesis can be viewed as a means of enabling the design process to view the construction process in a manner approaching HID terms. In doing so there is the potential for the design professional to be as creative as the capabilities and limitations of the labour resource will allow. In this sense a HID-style design aid can also be viewed as taking the more desirable preventative approach to the use of ergonomics. Pulat (1992) states clearly that a process is most effective when ergonomics is built into it, rather than being used as a corrective add-on after a problem has occurred.

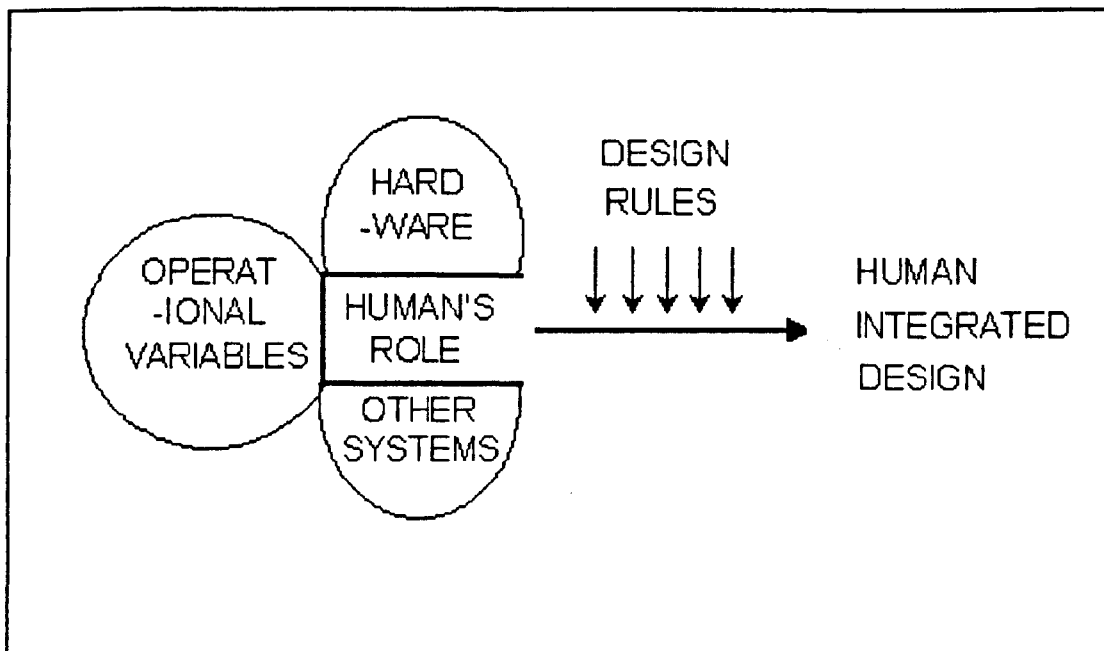


Figure 31. Operation of Human Integrated Design (HID)  
[Pulat (1992)]

The question arises as to how a HID-style approach could recognise the labour resource's capabilities and limitations. The result of the review was to conclude

that there was evidence within the literature for two approaches to the assessment of task difficulty; direct and indirect. A summary of the two is provided below.

**5.1.1 Task difficulty directly** Raouf, Tsuchiya and Morooka's work (1982) on the measurement of task difficulty in symmetrical and asymmetrical, small scale, manual tasks, indicates a possible approach to the assessment of construction task difficulty. The approach seeks to quantify the relationship between a given task and the symmetrical / asymmetrical hand movements required to complete the task. From such relationships other tasks can then be modelled, and times for the completion of those tasks can be predicted. An approach of this type is basically seeking to utilise the concept of predetermined motion time systems (PMTS). A PMTS assumes that an entire operation can be decomposed into a series of basic motions, each of which has a predetermined time value. The basic relationship considered by most PMTS is that between the distance moved, motion type and class, to produce a time-value for the 'reach' action [Karger, Bayha (1987)]. The work by Raouf et al produced a formula bringing together the factors affecting time values in such a way as to reflect the difficulty of each decomposed motion within a task. Raouf's task difficulty (TD) formula is:

$$TD = \log_2 2D/C \text{ bits}$$

where D = distance moved (mm), C = lateral clearance (mm), and bits are the rate of information transfer (see also chapter 7).

Raouf's technique presents a difficulty regarding use for larger construction

projects: it considers hand movements only in relation to fixed station assembly work typically completed within the area of a desktop workstation. For construction tasks the relationship of all body movements which are a response to carrying out the task may need to be quantified within the context of a larger, potentially more chaotic (in information terms) 'workstation'. A further problem is that task decomposition of this type requires considerable training and expertise to complete successfully; construction design professionals cannot be expected to develop such expertise.

Other work carried out by Raouf considered the impact of information load on the difficulty involved in carrying out given tasks. The resulting assessment was in the form of an index of difficulty [Raouf, Joseph (1986)]. Again, the tasks under examination were small-scale assembly tasks and reliant upon PMTS data for their analysis. However, more recent work regarding the advent of computer-aided workplace design reported by Raouf (1991), suggests that this problem is diminishing as PMTS become both more comprehensive and more compatible with computers. However, the problem of transferring an assessment method based on specific analysis expertise persists, therefore Raouf's general approach to the assessment of task difficulty cannot be directly adopted by this programme of research. The approach does demonstrate the possibility of assessing task difficulty purely on objective data, and thereby indicates that a design aid as proposed by the author is possible.

**5.1.2 Task difficulty indirectly** A number of techniques have been identified as possible bases for the objective, indirect assessment of task difficulty within

construction operations. None of the techniques were being used in connection with construction processes at the time of writing [Moore (1996a)].

5.1.2.1 Design For Assembly (DFA). Manufacturing industries consider levels of difficulty inherent in assembling products (assemblability) through the use of Design For Manufacture (DFM) and Design For Assembly (DFA) techniques, which were first used in the 1970s. DFA has become the most developed area within the study of assemblability, and proved itself capable of showing significant savings in both manual and automated assembly work. Within DFA there are three predominant methods available [Leaney, Wittenburg (1992)]:

1. *Hitachi "New AEM"*. Assembly Evaluation Method (AEM) bases its assessment of a design on the use of two indices; the assemblability evaluation score,  $E$ , and the estimated assembly cost ratio,  $K$ . Hitachi AEM does not have a facility to measure any action other than insertion in the assembly process. As far as construction industry tasks are concerned, this presents a significant limitation. Hitachi AEM is therefore discounted [Moore (1996a)].

2. *Lucas*. Developed by Lucas in conjunction with University of Hull, this is based on Hitachi. Lucas is not so widely used as Boothroyd. With regard to construction tasks, it has the disadvantage of requiring the user to produce an assembly sequence flowchart (ASF). The need to produce such a flowchart would detract from the adoption of a Lucas-based task difficulty assessment technique. In addition to this, there is also the problem previously identified for



Hitachi AEM regarding the limited range of actions which can be evaluated. Lucas is therefore also discounted.

3. *Boothroyd/Dewhurst*. Intended to advise designers on the difficulty of assembling their proposed products from the viewpoint of *rationalisation*. The Boothroyd method can be used in manual or software form. Boothroyd's evaluation mechanisms establish the cost of handling and inserting component parts. Emphasis is placed on the removal from a design of parts which are not fundamentally required; the design is effectively rationalised. There are several reasons why Boothroyd cannot be applied to the construction industry:

1. *Downward Movement*. The assessment of assemblability is based on the assumption that the predominant movement within the process of assembly is a downward one; manufacturing processes of desk-top scale, such as printed circuit board assembly, predominantly involve movements through the vertical plane. Construction tasks typically involve movements through the vertical and horizontal planes.

2. *Information Load*. Boothroyd creates a need to generate information which would not normally be available at the early design stage. This is generated by imposing a discipline of answering a long series of questions about the design. Construction industry design professionals would be reluctant to adopt any buildability strategy reliant upon such a discipline.

3. *Cost*. Boothroyd costs in the region of £25,000, depending upon the configuration specified. A complete CAD system can be purchased for around half this price. [Leaney, Wittenburg (1992)] A price of this level would act as a further discouragement to the majority of design practices.

[Moore (1996a)]

None of the above techniques are suitable for direct transfer to the assessment of construction tasks. Whilst their philosophy is in line with the suggestions for assessment of Task Difficulty as a means of advising on simplification, the

method of implementation is not wholly appropriate.

**5.1.2.2 Methods-Time Measurement (MTM) Techniques.** Three main levels of MTM are available (MTM1-MTM3), along with a number of specialist MTM systems for use in specific work situations such as MTM-C (Clerical) [Konz (1995)]. MTM techniques are a further form of PMTS as discussed previously. MTM techniques do not appear to have been applied to any great extent within the UK construction industry [MTM (1996)].

MTM1 is the most detailed technique regarding analysis of work and is therefore regarded as being the most accurate. MTM3 is a much simplified version of MTM1, is quicker regarding analysis but also gives less accurate results [Konz (1995)]. Sellie (1992) determined that to analyse a task using MTM1 would take in the order of 250 times the task's cycle time (in TMUs), whereas analysis using MTM3 would take in the order of 35 times the cycle time. Construction design professionals would not countenance such an investment of time within the context of assessing buildability.

Higher level MTM techniques (MTM3), are suggested by Konz (1990) as an alternative to Boothroyd on larger scale assembly work, such as car assembly. An important consideration is that extensive experience is required before the expertise needed to carry out the analyst judgements demanded by the use of higher level MTM techniques can be achieved. Without this expertise acceptable levels of analysis accuracy (at best + or - 20%) will not be reached [Konz (1995)]. In the search for accuracy, MTM techniques have become

complex to the point where they cannot be readily applied within a design aid such as is proposed within this research. Whilst the concept is suitable, the method of implementation is not. MTM techniques can therefore be discounted.

5.1.2.3 Computer-aided Workplace Design (CAWD). The development of CAWD has resulted in a range of systems becoming available. These systems may, or may not, be based around the predetermined motion times (PMTS) previously discussed. Systems operating at a small scale, such as desk-top assembly work, appear to make greater use of PMTS than those operating at a larger scale.

The prevalent use of CAWD is for larger scale ergonomic design work, such as the work carried out by Haslegrave and Homes (1994) on the integration of ergonomics and engineering in the technical design process. This work made use of workstation hardware and a simulation package known as SAMMIE to model the ergonomic factors related to lorry sleeper-cab use. No evidence has been found that SAMMIE, or any other CAWD systems, operate in an automated manner within the general design process. This lack of an automated analysis of the workspace, combined with the high cost of workstations etc., means that CAWD systems are not suitable for the analysis of construction task difficulty.

5.1.2.4 Job Severity Index (JSI). JSI was initially developed in 1978 to analyse lifting and lowering activities in manual tasks. Its premise is that the

severity of carrying out a given task is a function of job demands and the operative's job capacity. This function is then used to forecast the risk of injury to the operative whilst carrying out the task [Pulat (1992)]. The JSI approach is relatively simplistic, and whilst it may have undoubted benefits from a health and safety point of view, it does not appear to have any valid relationship to task difficulty assessment as defined within this thesis. However, in researching JSI further work identifying the factors which can adversely affect manual handling capability was located. The factors identified are noted in Figure 32.

<b>WORK CHARACTERISTICS:</b> Age Sex Motivation Physique, etc.	<b>MATERIAL CHARACTERISTICS:</b> Weight Bulkiness Load distribution Handles, etc.
<b>TASK CHARACTERISTICS:</b> Reach requirement Frequency of handling Duration, etc.	<b>WORK ORGANISATION:</b> Work-rest cycles Training, selection Job rotation, etc.

Figure 32. Factors affecting manual handling capability.  
[Adapted from Chaffin, Andersson (1984)].

Those factors which could reasonably be expected to be identified at the sketch design stage of a building's production are suggested as being: 'reach requirement', 'weight', and 'bulkiness'. The selection of these factors can be validated initially on the bases given in Figure 33. If this supposition that the majority of construction tasks fall into the category of manual handling tasks is accepted, then a factor which adversely affects operative performance on manual handling tasks in general may also be relevant to the assessment of

construction task difficulty. On this basis, the three factors identified above could prove useful in the development of the proposed design aid.

FACTOR	VALIDATION BASIS
Reach requirement	the designer will be dealing with the enclosure of space and can therefore be assumed to have begun locating the primary structural elements such as walls, floors, etc. Distances, and thereby reach requirements, can be determined, albeit in a relatively fluid form.
Weight	as the designer makes decisions regarding the textures and aesthetics of the space enclosures, material selection will at least be implied at the same time. A block wall, for example, has a different weight to a demountable partition.
Bulkiness	validated on the same basis as 'weight'.

Figure 33. Validation bases for selection of factors affecting manual handling capability in construction tasks.

5.1.2.5 NIOSH Recommended Weight Limit. A further technique for aiding the design of manual handling tasks is recommended weight limit (RWL), resulting from the American National Institute of Occupational Safety and Health (NIOSH) 1993 lifting guidelines. The basic concept of RWL is that the maximum load which can be manually handled, referred to as the load constant, is 23 kg. If an operative has to lift less than RWL in carrying out a task, the NIOSH guidelines would accept the task as being reasonable. RWL is calculated using the following formula:

$$RWL = LC \times HM \times VM \times DM \times FM \times AM \times CM$$

Where LC = load constant, HM = horizontal multiplier, VM = vertical multiplier, DM = distance multiplier, FM = frequency multiplier, AM = asymmetry multiplier, CM = coupling multiplier.

[Konz (1995)]

Determining values for each of the above multipliers requires further calculations to be carried out. There is a possibility that the use of multipliers for the horizontal, vertical, distance and asymmetrical components of manual handling tasks could be utilised in the context of those job severity index (JSI) factors selected previously (weight, reach required, bulkiness) in furthering the development of the proposed design aid. Determination of the coupling multiplier also involves the use of the decision tree included as Figure 34.

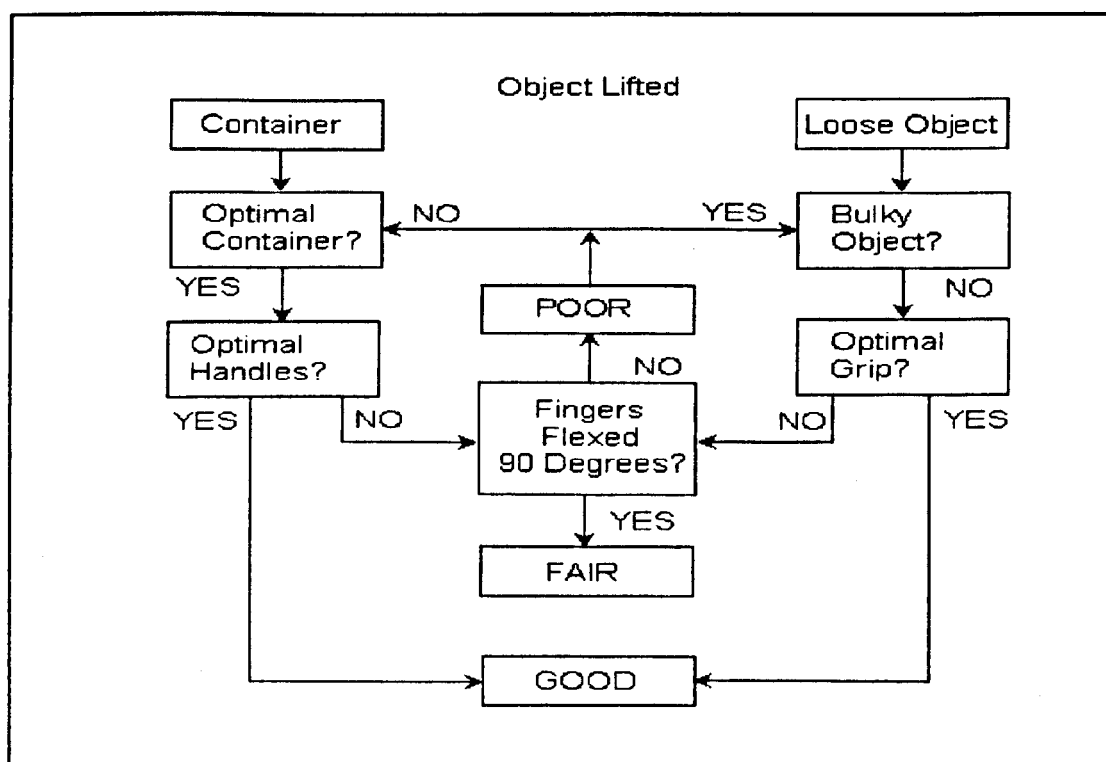


Figure 34. Decision tree for use with RWL.  
[Konz (1995)]

The use of RWL may be excluded by the presence of any one of thirteen characteristics within a task. Of these characteristics, it is possible that nine (see Figure 35) may be found in typical construction tasks.

NUMBER	CHARACTERISTIC
1.	Lifting/lowering with one hand
2.	Lifting/lowering while seated/kneeling
3.	Lifting/lowering in a constrained or restricted workspace
4.	Lifting/lowering cold objects
5.	Lifting/lowering of an unstable load
6.	Lifting/lowering while pushing, carrying or pulling
7.	Lifting/lowering with wheelbarrows or shovels
8.	Unreasonable foot/floor interface
9.	Unfavourable environment - temperature outside 19-26°C range

Figure 35. Characteristics ruling out RWL for use in construction tasks.  
[Konz (1995)]

However, a relevant factor regarding RWL in the context of assessing task difficulty is that there is consideration within RWL of the extent of control required over the object being moved or handled. The majority of construction tasks require significant control to be maintained over the material, component or sub-assembly being handled. 'Significant', in RWL terms, reflects the need to control an item at both the origin and destination of movement. The majority of construction tasks can be argued to require significant control of handling movements. The analysis of lifting movements requiring significant control necessitates an increased input of information, summarised in Figure 36, to the RWL calculations. Such a comprehensive list of required information would prove detrimental to the adoption by design professionals of any task difficulty assessment technique operating on such a basis. The basis of this suggestion is that design professionals do not generally possess expertise in the

application of RWL in a construction industry context. Obtaining the required information would therefore represent an additional burden on the designer.

INPUT No.	INPUT REQUIRED
1.	Initial horizontal location of the hands from the ankle midpoint
2.	Initial vertical location of the hands
3.	Initial angle of asymmetry of object centre
4.	Vertical travel distance between the origin and destination
5.	Frequency of lifts per minute
6.	Lifting duration (hr) and recovery time (hr)
7.	Hand-container coupling classification (use decision tree)
8.	Final horizontal location of the hands
9.	Final vertical location of the hands
10.	Final angle of asymmetry of object centre

Figure 36. Information inputs required by RWL for analysis of significant control movements.

[Konz (1995)]

In order to simplify the use of RWL, NIOSH software, which will carry out the required calculations, is available. A copy of this software was purchased from the University of Kansas for evaluation by the author. The software is not automated and requires the user to input the data needed to complete the calculations. Whilst this may be acceptable when RWL is being used by experienced practitioners, such an approach would not be acceptable for use by architects and others. Likewise, the output from the program is not in a form which is readily understandable to novice users (sample output included as appendix four). The implementation of a RWL based assessment technique



would therefore need to utilise a simplified approach, with reduced information input requirements, and/or be automated so as not to require the development of specific ergonomic analysis skills. Furthermore, the results of the assessment should be presented in such a manner as to allow the user to develop expertise regarding buildability, not ergonomics. The case against the general use of RWL in a construction context is argued as being a strong one. However, the use of multipliers may be of value in developing the proposed design aid.

*5.1.3 Sub-section conclusion* The techniques intended for direct assessment of task difficulty are too constrained in terms of workspace capabilities for current use/adaption within the context of this research. Such techniques typically operate within desktop-sized workspaces. However, the concepts upon which they are based suggest that the use of objective data only in the assessment of difficulty within tasks typical of the construction process is possible.

The most developed techniques with regard to assessment of assembly difficulty are those which are not specifically intended to assess task difficulty; the DFA techniques. However, DFA techniques in general were suggested as being inappropriate for direct transfer to construction processes.

The most detailed assessment technique was identified as being the NIOSH recommended weight limit (RWL). Whilst a significant number of characteristics which would preclude the use of RWL were identified regarding construction

tasks, it was noted that the use of RWL-style multipliers could possibly be of benefit in conjunction with the reach required, weight and bulkiness factors (of materials, components and sub-assemblies) used in the job severity index.

No existing techniques suitable for immediate use in assessing task difficulty in construction process operations were identified within the areas of work study and ergonomics.

## **5.2 Other approaches.**

A number of other approaches, outside the areas of work study and ergonomics, were examined. These were predominantly subjective, rather than objective, assessments and therefore did not strictly fall within the scope of the initial literature review.

**5.2.1 Concept differential.** Moore (1990) surveyed the opinions of experienced roofing contractors regarding the difficulty of completing given roof details. This investigation aggregated subjective assessments and indicated the recognition, by experienced construction personnel, of varying difficulty within given roofing tasks. The survey indicated a low level of what is referred to by Moore (1993) as concept differential (level of 'independence'; see chapter one) regarding task difficulty in an area where respondents were experienced. This suggests there are design features which indicate increased production difficulty to those with sufficient expertise to recognise them. Valleys, for example, were noted by all respondents as being a difficult design feature to produce on-site. Identification of such features is an objective of the proposed

design aid. The work on concept differential does not, however, suggest any means, other than spatial relationships in the work area, by which task difficulty could be assessed objectively.

*5.2.2 Modelling The Human Operative.* The majority of the work in this area deals the modelling of how an operative controls given automated production processes. Norros, Ranta and Wahlström's (1982) work on operative actions whilst seated at nuclear power station control panels/desks is typical. Generally, this area of work emphasises the type of analysis required for control panel design.

However, the author carried out some basic attempts at modelling the relationship between human limbs and degrees of freedom at limb joints, during the early stage of this research programme [Moore (1993a)]. The modelling was an attempt to determine the extent of any mathematical relationship governing movement of the human body, with a view to using such a relationship as the basis for representing the human worker's interaction with a physical workspace. Standard anthropometric data was used to produce a scaled line model of a 'typical' male operative (for male anthropometric data, see appendix five) which was then 'moved' through the range allowed at each limb joint. Generally, the approach was similar to that adopted by those CAWD researchers designing larger scale work places, such as Kayis, Iskander (1994), but without the benefit of sophisticated hardware.

The model is shown as Figure 37, and incorporates the three cardinal planes



instruction, such as the formula presented below.

$$C1 = -14.1 - 0.818C2 + 0.300C3 + 0.190C4 + 0.149C5$$

This model represented the wave of movement resulting from a 'reach' action cumulatively taking up the maximum movement in the hand, forearm, upper arm and spine. The R-square (adjusted) values for such models were typically around 95 - 98% which the author suggests would prove sufficiently accurate as a basis for the proposed skill modelling process [Moore (1993b)].

The data represented by the model was intended for eventual use in an automated form of a process, suggested by the author, referred to as skill modelling [Moore (1993b)]. The basic concept of skill modelling is the premise that rules governing core movements, common to physical tasks, can be identified, assessed and placed in a knowledge-base. Such a premise regarding core movements is not unlike the seventeen micro-motions, or therbligs, which formed the basis of the Gilbreth's analysis of work methods [Gilbreth, Gilbreth (1923)].

An example task would be the shortening of the arm in order to bring an object closer to the operative. Movement on each joint is defined as a percentage of total possible movement on that joint. By allowing consideration of translation (movement) in any, or all, of the three primary axes (x,y,z) combined with rotation in any, or all, of the three cardinal planes, it was suggested that a 'wave' of movement could be modelled, thereby producing a basic

representation of an operative's actions whilst completing a given task [Moore (1993a)]. Similar approaches to human modelling have been developed elsewhere, a suitable example being the work on a 3D human model for use in work place ergonomic analysis by work-station based CAD systems such as IBM's CATIA [Kayis, Iskander (1994)]. Such a representation provides a possible basis for: the modelling of those on-site tasks required of the constructor by the construction process; evaluating the difficulty of each task, and informing the designer of tasks which would be expected to hinder buildability. Once informed, the designer has the opportunity to simplify the design at the sketch design stage, thus avoiding later problems on-site.

The key to the successful skill modelling was suggested as being the satisfactory development of skill concept packages which would control the assembling of movements so as to represent a given task [Moore (1993b)]. Such packages may possibly be enhanced by the use of multipliers, as used within the RWL calculations discussed previously.

*5.2.3 Sub-section conclusion* Anthropometric modelling of the human operative's actions within a defined work-space, whilst carrying out given tasks, appears to provide a basis for the further development of skill modelling. Skill modelling itself suggests the potential for determining, at the task level, values for a design's level of buildability within the proposed ADA. A contribution to the development of a control mechanism for skill modelling may exist in the form of multipliers used in RWL analysis.

5.3 Skill.

The literature on skill definition and assessment presents a wide range of possible interpretations as to what can be taken as being 'skill'. Moore (1993a, 1996a) has discussed those interpretations which are significant, with regard to this thesis, and these discussions are summarised below.

5.3.1 *Novice to Expert.* Dreyfus and Dreyfus (1980) suggest that skill can be represented by the development of an individual from the novice level to the expert level. As a novice, the individual possesses virtually no ability or knowledge of the skill being learned. This situation improves as the novice moves through three subsequent intermediate stages before reaching the stage of being expert. Within this process are important factors regarding the individual's development which are summarised in Figure 38.

FACTOR No.	CHARACTERISTICS OF FACTOR
1.	the movement from reliance on abstract principles to the use of past concrete experience as paradigms
2.	a change of perception in which the demand situation is seen less and less as a compilation of equally relevant parts, and more and more as a complete whole within which only some parts are of relevance
3.	the progression from being a detached observer outside the performance, to being an involved performer within the performance of a skilled task

Figure 38. Factors in the development of an individual from novice to expert. [Benner (1989)].

Whilst such factors have a relevance as far as the selection of operatives for tasks requiring particular levels of skill, they do not appear to present the basis

of a means of objectively assessing task difficulty without the input of someone who has achieved an equal, or greater, level of expertise to that required to complete the task. As such, the work by Dreyfus and others does not represent a suitable basis for the development of the proposed design aid.

**5.3.2 *Micro-skill.*** The work by the Gilbreths took a particularly narrow viewpoint of skill, which resulted in them emphasising the importance of the fourth dimension; time. They were particularly concerned with the 'relativity of simultaneity' which was manifest in the actions of a process operative in terms of the 'lateness' of various anatomical members. This concern resulted from the observation that an important relationship existed between the motions made by various members of the body as they moved in time, and in relation to each other. The intention was to use this relativity of spontaneity to remove wasteful movements from the carrying out of a task and ultimately to achieve 'superstandardisation' [Gilbreth, Gilbreth (1923)].

The important aspect of the Gilbreth's work, with regard to this thesis, is that they identified, possibly for the first time, that skill could not satisfactorily be measured in terms of the operatives movements through the three dimensions of space. There also had to be consideration of efficient use of the time element, or fourth dimension, when measuring skill. This is relevant to the discussion, in the following section, of Welford's definition of skill. In fact, the Gilbreths postulated that a fifth, or even sixth, dimension may be required to satisfactorily record skill.



Unfortunately, the techniques developed by the Gilbreths for the required measurement of an operative's actions (the use of chronocyclographs) do not appear to be possible to automate. No evidence was located by the author in the literature which suggested that such automation had been achieved, or would be feasible. The Gilbreth's techniques therefore appear to suffer from a similar problem to the MTM techniques discussed previously; high levels of assessor expertise are required before they can be used to any value.

**5.3.3 Accuracy, Rapidity, Competence.** The literature focusing on the psychological aspect of skill supplied a possible approach to assessing the level of task difficulty. Welford's (1968) definition of skill, with its basis in the relationships between rapidity, competence and accuracy, is suggested by the author as being particularly relevant because all three components have the potential to be assessed objectively, and also allow consideration of operative movements through the four dimensions [Moore (1996a); Moore, Tunnicliffe (1995)]. Moore (1993b, 1996a) suggested that the development of skill concept packages, within the previously mentioned technique of skill modelling, should be based on the combining of accuracy, rapidity and competence data, as being a representation of skill.

A possible benefit of using objective rules concerning accuracy, rapidity, and competence is suggested by the author as being that some of the quantifiable aspects of good aesthetics will also be covered. In this manner, the inclusion of subjective values, such as purely aesthetic implications, which can confuse the issue of what is good, or bad, buildability may be justifiably declined.

**5.3.4 Manual Tracking Tasks .** Within the area of cognitive psychology, skill is described in terms of visually searching the workspace and responding appropriately to the stimuli identified during that search [Eysenck (1994); Brogan (1988)]. Krendal and McRuer (1959) carried out research on skill expressed in terms of ability to complete manual tracking tasks, part of which relied on the ability to model anticipated future changes within the visual space being searched. This can be likened to aspects of the development of expertise proposed by Dreyfus and Dreyfus discussed previously. Construction tasks can largely be regarded as manual tracking tasks because of the imposition on the operative to repeatedly visually search the workspace.

**5.3.5 Sub-section conclusion.** Of the literature regarding skill in the carrying out of tasks, the most relevant to this programme of research is that related to the consideration of accuracy, competence and rapidity. An additional consideration is suggested as being the possible relevance of manual tracking research to the functionality of the proposed design aid.

## **5.5 Conclusions.**

A range of possible bases for the assessment of difficulty in carrying out given construction tasks has been examined. These bases can be categorised as assessing task difficulty directly or indirectly.

- \* No pre-existing methods for the assessment, either directly or indirectly, of difficulty involved in the completion of construction tasks were identified. This resulted in the literature for industries other than

construction being researched.

- \* Of those bases which represent existing methods of directly assessing task difficulty of work in industries other than construction, none were found to be directly transferable to the assessment of task difficulty in construction work.
- \* Those bases representing existing methods of indirectly assessing task difficulty in other industries, *such as design for assembly (DFA)*, were found to be inappropriate for direct transfer to the assessment of task difficulty in construction work.
- \* Several of the concepts utilised by existing techniques for direct and indirect assessment of task difficulty in other industries were identified as relating to the philosophy of the proposed design aid.
- \* The use of standard anthropometric data was found to allow basic modelling of an operatives range of movements in completing a task within a given workspace. This may prove relevant to the development of skill modelling as a basis for assessment of task difficulty.
- \* The work found to have the most potential as a basis for the assessment of construction task difficulty was that of Welford, with particular reference to the use of accuracy, competence and rapidity in defining and measuring skill. There is the possibility that this work can

be enhanced, within the context of skill modelling and skill concept packages, by the consideration of factors such as: job severity index manual handling capability factors of 'reach requirement', 'weight' and 'bulkiness'; movement multipliers such as are used in the recommended weight limit approach for movements requiring significant control; a consideration of manual tracking research with regard to operative expertise in visually searching the workspace.

The proposed design aid is therefore represented at this stage by an indeterminate mix of the factors identified in the conclusions above. This representation will be further investigated in chapter six through a consideration of possible frameworks within which the functionality of the proposed design aid can be structured.

## 6. INITIAL DEVELOPMENT OF A TASK DIFFICULTY ASSESSMENT MODEL FOR A CONSTRUCTION HIGH LEVEL TASK.

*In modern psychological terms, the kinds of functions required of man in ... work situations include (1) the discrimination and identification of sensory inputs, (2) the receiving, processing, storage, and retrieval of information, and (3) the exercise of control actions that range from discrete binary key-presses to continuous-control guiding or steering actions (tracking).*

[Bilodeau, Bilodeau (1969)]

It has been proposed that the design aid will be required to 'construct' knowledge regarding the construction processes being assessed, rather than referring to a pre-existing database of process knowledge. The prototype automated design aid (ADA) will therefore require to be more sophisticated in its use of knowledge than present expert, or knowledge-based, systems in this field. Lueprasert and Skibniewski (1994) have recognised the difficulties regarding knowledge acquisition for the development of expert systems in the domain of buildability, stating that traditional knowledge acquisition techniques may not represent a suitable approach.

### 6.1 Theoretical Framework To The Proposed ADA

The context of the hypothesis put forward in chapter three has been further developed and revised as a result of subsequent research. The revised hypothesis now states:

The production of a skill modelling based Automated Design Aid, to be used at sketch design stage, and within a CAD environment, would allow task level buildability to be improved through a simplification strategy managed by the communication of appropriate knowledge from construction process workers to design process workers.

Because there is no intention to communicate design process knowledge to construction process knowledge workers within the hypothesis, there is effectively only one main variable for the proposed ADA to deal with; that knowledge which is deemed appropriate to be communicated from the construction process knowledge worker to the design process knowledge worker. This communication is reliant, within this thesis, upon acceptance of the concept of skill as being a possible basis for both the identification of that construction process knowledge which is to be communicated, and the assessment of buildability. Three component data variables of skill knowledge have been identified; *accuracy*, *rapidity* and *competence*, from which Moore (1993b) suggests an appropriate skill model can be assembled. The skill model to be assembled will vary with the construction process undergoing buildability assessment.

The theoretical framework supporting the organisation of the proposed skill modelling technique can be considered under two headings: first generation expert systems, and generic task knowledge based systems (KBS). Within the context of this thesis 'expert systems' refers to first generation, assembly language based constructs. 'Generic task KBS' refers to second generation artificial intelligence (AI) constructs.

**6.1.1 Expert Systems.** One approach to the execution of skill modelling would be to develop an appropriate expert system. The expert system differs from a conventional computer programme in that it manipulates knowledge rather than data, hence the alternative title of knowledge system [Coombs,

Franks (1990)]. A further variation is the feedback system, as discussed previously.

Expert systems have been utilised successfully in a number of applications domains, or areas of knowledge, particularly the domain of diagnosis. Such systems encompass four levels of knowledge representation: structural; behavioural; functional, and pattern matching. It is also possible to link common elements of two or more knowledge bases within a framework to build multiknowledge based systems [Morizet-Mahoudeaux (1991)]. Whilst the buildability assessment problem is suggested as one requiring a multiknowledge response, a multiknowledge based expert system may not be the most appropriate form for that response.

An important first step in reaching a conclusion on this is to determine which level of knowledge the system will need to attain, rather than represent; surface (heuristics, facts); domain / procedural models, or deep (laws, principles). Present expert systems technology does not allow for the creation and use of deep knowledge. A simple rule based system will create surface knowledge and a more sophisticated hybrid system allows the creation of domain / procedural knowledge. The majority of construction industry design, planning and scheduling systems rely on domain or procedural models [Coombs, Franks (1990)].

A significant recurring problem regarding expert systems is that of knowledge acquisition, or elicitation, in the area of construction processes. Bowen and

Erwin (1990) identified knowledge acquisition as being the major bottleneck in developing expert systems. Fischer (1991) noted that, in the construction area "...solid lessons are very difficult to extract." Kartam (1996) adds that the knowledge acquisition and validation processes are complicated by difficulty in achieving a consensus on the best method(s) of compiling information from the variety developed by individual project managers. An expert system approach to skill modelling would be dependant upon the required system not being reliant upon the creation of deep knowledge. This is aside from the possibility that the buildability problem is simply a poor domain for the use of an expert system, as suggested by Lueprasert and Skibniewski (1994). Characteristics of a poor expert system problem are summarised in Figure 39.

1. The cost of a bad decision is high; the UK construction industry has previously been suggested as losing possibly many millions of pounds each year through buildability related bad decisions.
2. Solutions are based upon unpredictable or poorly understood factors (see Kartam's comments re design professionals knowledge of construction processes).
3. The task requires common sense.

Figure 39. Characteristics of a poor expert system problem.  
[Duchessi and O'Keefe (1992)]

The buildability problem appears to be simply a bad expert system problem. One possible means of resolving the difficulty with regard to knowledge elicitation is the work by Tunnicliffe and Scrivener (1991), which suggests an approach of separating the knowledge elicitation phase of system development from the constraints of given machine-dependant structures (e.g. rules, frames, networks etc). Such an approach is suggested by the author as more typical



of generic task KBS than of expert systems.

The extent of the knowledge required by the proposed ADA is discussed further in section 6.1.3. However, there does appear to be support within the literature for the concept of what may be referred to as elements of generic knowledge. An example of this can be found in Welford's (1976) assertion that the understanding of skill performance depends upon the human capacities, and the demands of the external environment in which the skill is being performed, being measured in the same terms. This consideration of the external environment can lead into the fields of cybernetics and ergonomics. An expert system constructed in such a manner would represent a second generation system capable of expert competence, rather than simply modelling expert performance as do current (first generation) expert systems.

Expert competence regarding construction tasks can be considered in terms of the brain's ability to model external events without having to act them out. With regard to the exhibition of skill, the ability of an individual's brain, or 'neural machinery', to extrapolate from present data, and test the consequences of various possible lines of action, can be argued to be reflected in the success with which a given problem is solved [Welford (1968)]. McRuer and Krendel (1959) developed the work of Craik (1947) further in their research on the learning of manual tracking tasks. They found the learning process for manual tracking tasks (the majority of construction tasks contain elements of manual tracking) was comprised of three phases. The third of these phases concerned the development of precognitive behaviour, with the argument being that such

behaviour was dependent upon the creation of deep knowledge. Such knowledge cannot be created within first generation expert systems. Once again, there is the suggestion that the intellectual abilities involved in deciding upon appropriate actions in changing circumstances are an important aspect of skill. No evidence was located within the literature to support the use of an expert system in a manner which could be classed as exhibiting precognitive behaviour. The use of an expert system is therefore inappropriate to the development of the proposed design aid.

6.1.2 *A Generic Task KBS Approach.* Concepts of skill will vary with both the values of individuals and the circumstances in which they operate. Clarke (1983) saw skill as being traditionally defined in terms of cartesian principles. Welford (1976) however, suggested that the higher levels of crafts skills are concerned with the translation mechanism, whereby decisions are made as to what should be done under particular circumstances. Higher level skills therefore depend less on the ability to execute given manual tasks than on the ability to decide which tasks require to be executed, and are more akin to the intellectual skills exhibited by administrators and managers. Such intellectual skills are argued to relate to ideas and principles; skill is therefore not a constant in that it responds to production 'environment' changes. Principles are seen as being examples of deep knowledge with regard to the operation of expert systems, thus increasing doubt regarding the viability of an expert system based approach to the technique of skill modelling: the alternative approach of utilising a generic task KBS may prove to be more relevant.

Current approaches (to the development of general KBS) noted within the literature typically involve development of a knowledge construct which is able to identify, extract, and utilise both explicit and implicit data in a flexible manner, so as to respond to changes in the production environment, ie. be capable of expert performance. The proposed design aid also seeks to achieve expert performance, but has the additional aim of operating on the basis of a minimal quantity of knowledge. A possible means of achieving these aims will be initially examined through the consideration of Chandrasekaran's (1983, 1986, 1987, 1988) generic task (GT) approach.

Chandrasekaran's work aims to move the development of expert systems away from the assembly language, first generation approach, and towards the artificial intelligence (AI), second generation approach through the development of generic tasks. This is generally referred to as a higher level approach. The following discussion of GTs is largely summarised from Chandrasekaran (1988), where it is suggested that a GT is both a strategy for a task, and a task in itself. An example of this concept is that diagnosis is one strategy for making patients feel better, but it is also a task for which many expert systems have been designed. GT characteristics are identified in Figure 40.

- |   |
|---|
| <ol style="list-style-type: none"><li>1. Kinds of information taken as input for the task, and the information produced as a result of performing the task. These define the functionality of the task.</li><li>2. A vocabulary of knowledge types as part of a way to represent and organise the knowledge needed to perform the generic task.</li><li>3. A vocabulary, provided by the process (algorithm, control, problem solving) that the task uses, for inference and control of the task.</li></ol> |
|---|

Figure 40. Characteristics used for identifying generic tasks.  
[Chandrasekaran (1988)].

Example GT problems, along with task specifications defining the functionality of the task, and the generic task tool used to structure the solution to the problem are provided in Figure 41.

GENERIC TASK	TASK SPECIFICATION	GT TOOL
Hierarchical Classification (Medical Diagnosis)	Input: a situation description in terms of features. Output: classify it, as specifically as possible, in a classification hierarchy.	CSRL - Conceptual Structures Representation Language
Knowledge-directed Information Passing (Diagnostics based upon converted sensor or chart values)	Input: given attributes of some data entries. Output: determine the attributes of other data of interest, but not directly known (can be inferred from the available data).	IDABLE - Intelligent Data Base LanguageE
Synthesis by Plan Selection and Refinement (Designing an object by hierarchical planning)	Input: given specifications of the object to be designed. Output: generate design of an object meeting the specifications.	DSPL - Design Specialists and Plans Language.

Figure 41. Example GT problems, specifications and GT tools.  
[Summarised from Chandrasekaran (1988)].

A further consideration is that problems classed as non-trivial, such as design, planning and diagnosis, may require decomposition into subproblems. Each subproblem would match the functionality of a given GT, with the result being a complex generic task KBS produced using a tool set, rather than a single tool, as is more typically the case in knowledge engineering environments. In response to these points an initial GT framework for the problem of assessing

buildability, which is defined in terms of specific subproblems, is outlined in Figure 42.

GENERIC TASK SUBPROBLEM	TASK SPECIFICATION	GT TOOL
Identify range of craft operations explicit in a given design eg. roofing	Input: selected portion of a CAD design. Output: list the total range of recognised craft operations in the design portion being examined.	Not yet known. Possible use of buildability attributes
Identify artifacts to be constructed by each craft operation	Input: naming conventions used for individual CAD file layers within the given design portion. Output: groups of artifacts to be produced, defined in terms of explicit information; length, height, width, etc.	Not yet known. Possible use of buildability attributes
Identify implied knowledge regarding each artefact relevant to buildability assessment	Input: skill data held within individual skill concept packages combined with relevant buildability attribute data. Output: task difficulty assessments for each artefact within the given design portion.	Not yet known. Possible use of buildability attributes
Summarise individual artefact assessments to give overall buildability assessment	Input: task difficulty assessments for individual artifacts. Output: overall buildability assessment for the design portion being examined.	Not yet known

Figure 42. Initial GT subproblems and specifications for the problem of buildability assessment.  
[Chandrasekaran (1988)]

A key factor in determining tasks suitable for a GT approach is that they should have a coherence and simplicity characterisable by a simple type of knowledge, and a family of inference types. This factor allows the GTs to function as 'building blocks' for the assembly of an information rich KBS (the author

suggests that an information rich KBS is not the same type of construct as a knowledge abundant expert system). An example of the building block approach is given in the GT architecture used by Chandrasekaran for the problem of diagnosis. The architecture comprises: hierarchical classification; hypothesis matchers; abductive assembly; knowledge-directed data abstraction and inference, with each of the modules being classed as generic. Figure 43 illustrates the terms in which 'generic' is defined.

1. a strategy independent of diagnosis and can be used in a number of other high level tasks. The abductive assembler, for example, can accept input from a plan recogniser, and the data abstractor can be used by a therapy planner.
2. a user of characteristic knowledge and inference, making it possible to focus the problem solving effort in a manner appropriate to the task.

Figure 43. Terms defining a generic module

Chandrasekaran states design to be in general complex, and a relatively poorly understood activity, from the viewpoint of artificial intelligence (AI). However, his suggestion that design problem solving should be viewed as having two sets of parts is particularly relevant to this thesis. The two sets of parts are identified as those that propose, or generate, designs, or parts of designs, and those that test, analyse, critique or evaluate the proposed design. The ADA proposed in this thesis is intended to function as one of the second set of parts, but lies outside the area focused on by Chandrasekaran: GTs in relation to the generation of designs, within an AI environment, through the medium of a KBS. However, the use of GTs to break down complex problems into less complex subproblems, appears to be a suitable strategy for progressing development of

an ADA dealing with the assessment of buildability problem.

The most significant constraint to the ad-hoc adoption of GTs in the form described by Chandrasekaran relates to both the machine specific nature of GT tools (Xerox 1100 series LISP machines), and of AI languages generally [Pateman (1992)]). Given that the hardware base for the proposed ADA has been determined as PCs, the use of generic task tools to control the *assembling of generic modules is not seen as being possible*. The author therefore suggests that the GT philosophy be adapted for use in a PC environment.

Moore (1995) developed a model (see Figure 44) describing a possible functionality, which reflects the preceding work in this thesis, for the proposed design aid. This model was based upon four modules, with each utilising GTs to solve subproblems in the assessment of buildability at the task level. This model was dependent upon knowledge relationships between the four modules. The knowledge relationships within the proposed ADA were structured in accordance with outline GT theory, in that the knowledge to be communicated was appropriate to the tasks identified within the design being assessed, eg a bricklaying task requires bricklaying knowledge. Such tasks are considered high level tasks (HLT) by GT theory, with each HLT utilising a number of generic tasks, eg levelling.

## **6.2 Proposed ADA Structure.**

This structure has been revised as a result of further development work carried

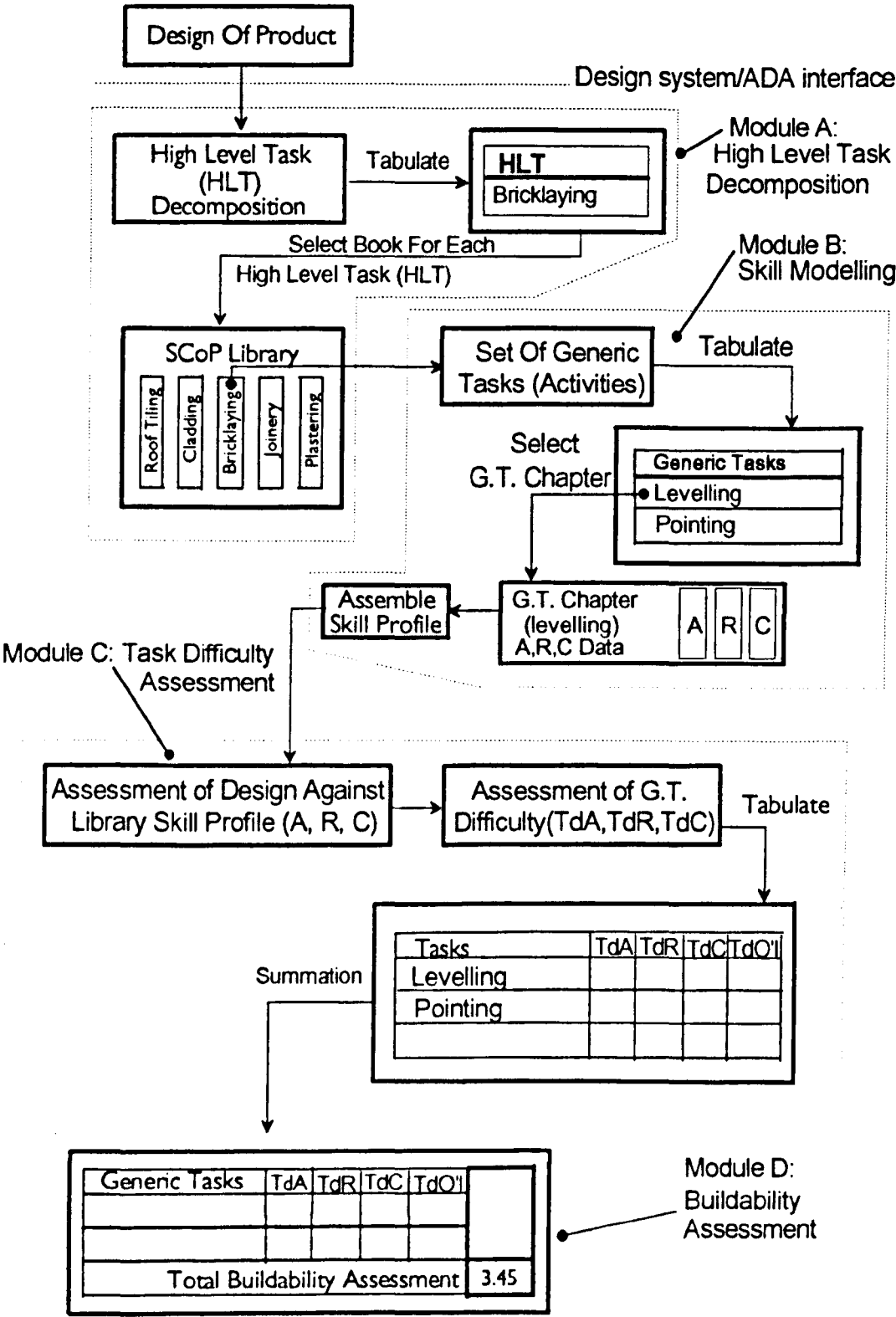


Figure 44. Proposed ADA (Moore, Tunnicliffe (1994(a))



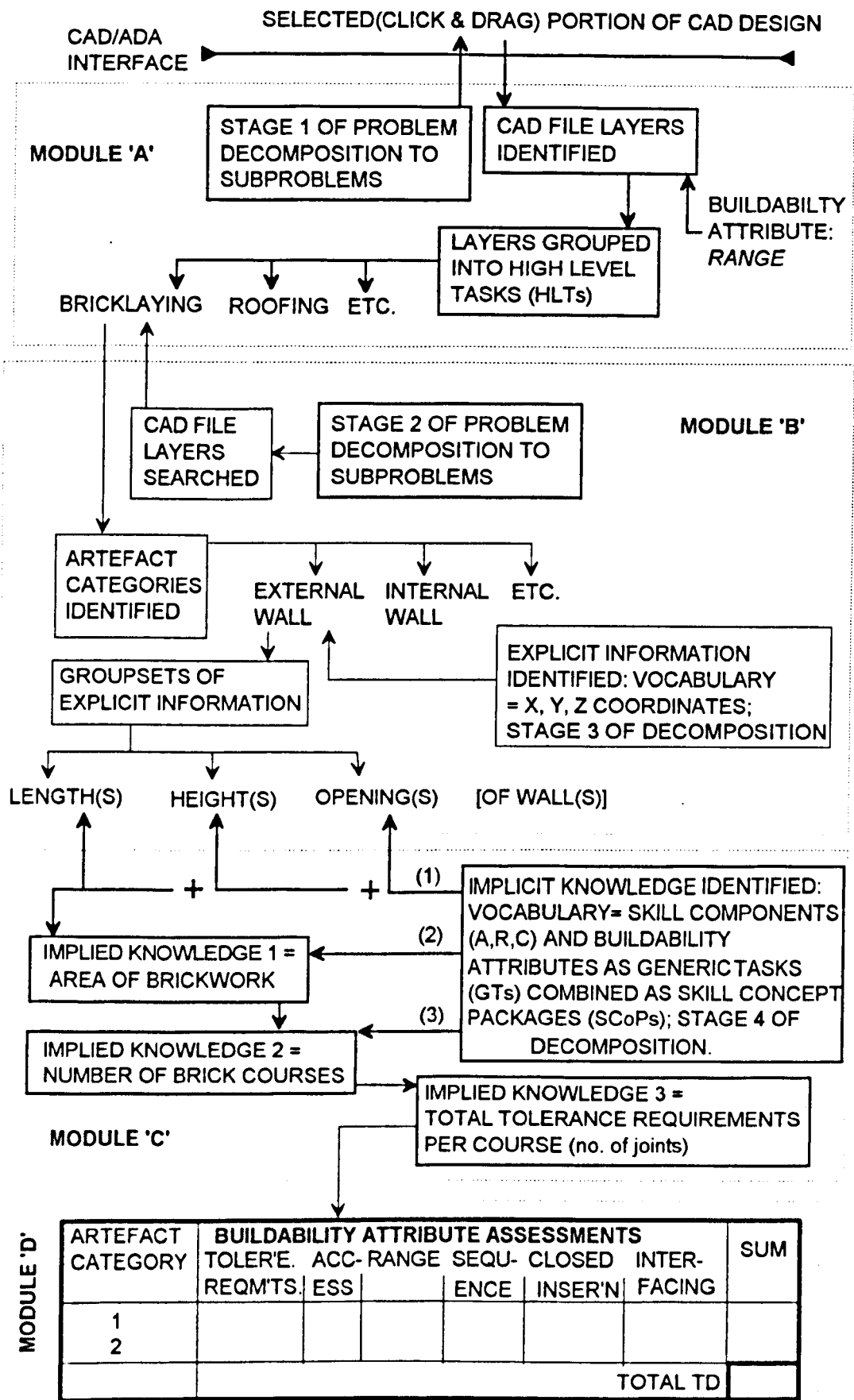


Figure 45 Revised ADA Structure

out by the author, becoming somewhat simpler than the initial structure, due to the removal of redundant components, and the rigorous application of GT theory. Redundancy was identified on the basis of a function being effectively repeated in more than one module. Figure 45 shows the revised structure of the proposed ADA, and the following discussion relates to that structure.

**6.2.1 Module A: High Level Task Decomposition.** The designer selects some portion of their CAD design for assessment, and then initiates the ADA through the use of drop-down menus within AutoCAD. The ADA will then instruct module 'A' to examine the selected design portion (which represents the task information input: one aspect of GT characteristic 1) for artifacts which represent one or more high level tasks (HLTs). Such artifacts will exist within the selected CAD design portion in the form of annotation to one or more layers of the CAD file. CAD layer naming conventions were discussed in chapter four, and a possible method of searching file layers was illustrated as Figure 30. Use of layer naming will indicate to the ADA which HLTs are required to construct the selected design portion. In this manner, the problem of buildability assessment is decomposed initially into a subproblem of HLT identification. For example, layers named as being brickwork will cause module 'A' to access the HLT of bricklaying. All HLT within the design portion will be identified through the use of a vocabulary based on the buildability attribute of 'range'. As a means of ensuring relevance, the identified HLT will be tabulated and displayed for the designer to check, thereby completing stage 1 of the problem decomposition, prior to Module 'B' being initiated. The same vocabulary will then be used to construct basic knowledge regarding the

artifacts involved, in module 'B'.

6.2.2 *Module B: Skill Modelling.* After displaying the table of HLT identified by Module 'A', the ADA proceeds to Module 'B'. This module commences the construction of buildability knowledge regarding the design portion through use of the attribute vocabulary. Figure 46 illustrates suggested named CAD file layers for a sample design portion.

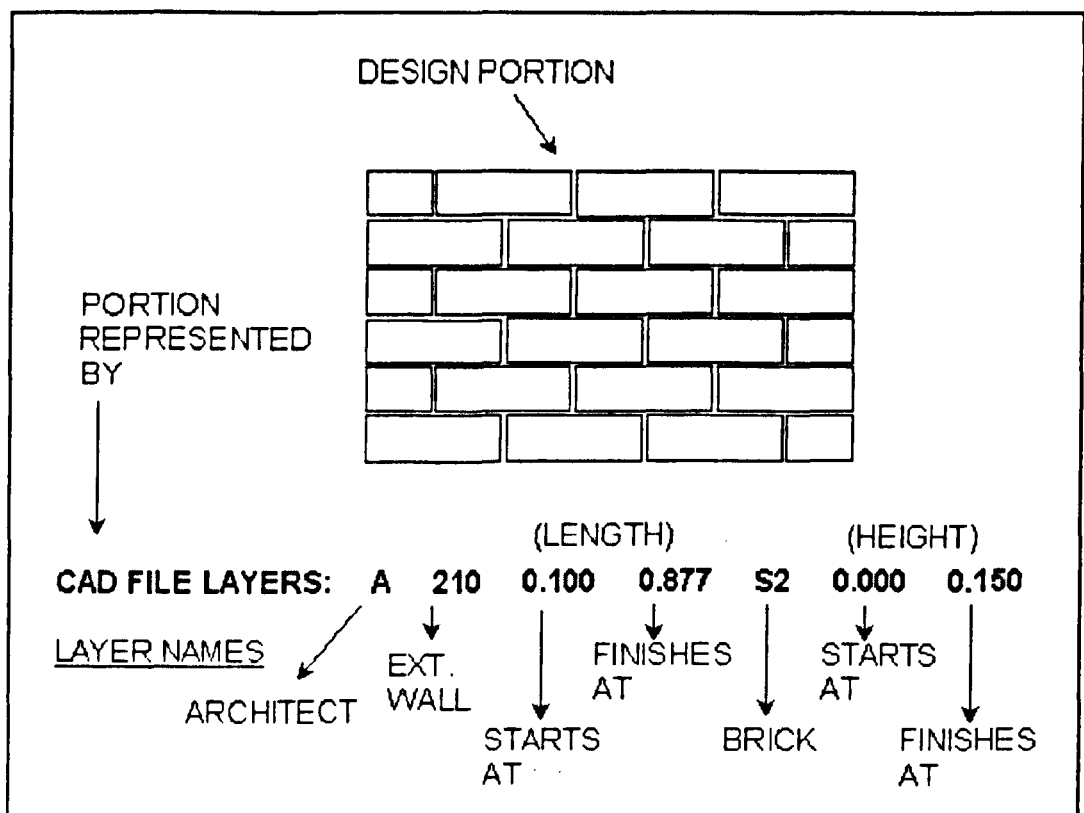


Figure 46. Suggested named layer representation of sample design portion. [Developed from: Autodesk (1993)]

The attribute vocabulary will search these layers for information relevant to each HLT, in this example bricklaying, for names which identify artifact categories. By reading the layer defining the category of artifact, the

vocabulary 'knows' it is dealing with an external wall, and that there are certain implications attendant to such an artifact: a wall requires to be validated during its construction against explicit x, y, and z coordinates, thereby demanding the skill component of 'accuracy' be invoked in module 'C'. The 'accuracy' component in turn invokes the buildability attributes (or GTs) of: 'tolerance requirements' (TR); 'access', and 'interfacing' (if there is more than one HLT within the selected design portion). Artifact identification will complete stage 2 of the problem decomposition into subproblems. Problem decomposition stage 3 requires module 'B' to further search the CAD file layers to identify explicit information regarding each named artifact category. This information will typically be in the form of x, y, z coordinates, and will be placed into groupsets, each one representing a key feature of the artifact; length of walls, height of walls, openings in walls, etc. At this point, module 'C' will be initiated.

**6.2.3 Module C: Task Difficulty Assessment.** This module will be where the ADA will form the required knowledge constructs regarding the design portion. Previous modules have extracted explicit information; this module will construct implied knowledge. Within this section of this thesis, the author defines 'knowledge' in terms of a range of information brought together in such a way as to produce data which was not previously explicit. The author proposes that this be achieved through a combining of skill components (accuracy, rapidity, competence), and buildability attributes acting as GTs. Moore (1993a) has suggested that relevant skill components be controlled by appropriate skill concept packages. Such packages may also be used to categorise germane knowledge resulting from the application of particular

buildability attributes. Thus the knowledge resulting from application of the buildability attributes of 'tolerance requirements', 'access', and 'closed insertion' would be appropriate to the skill component of accuracy. These attributes effectively become the vocabulary for the skill concept package related to assessment of accuracy. Vocabularies for each of the skill components are illustrated in Figure 47.

SKILL COMPONENT	BUILDABILITY ATTRIBUTES FORMING RELATED SKILL CONCEPT PACKAGE
Accuracy	Tolerance Requirements / Access / Closed Insertion
Rapidity	Interfacing / Tolerance Requirements / Access / Range (only used as an indicator of project complexity: the greater the range, the more complex the project)
Competence	Sequence / Interfacing / Tolerance Requirements

Figure 47. Suggested skill concept package vocabularies.

Figure 45 illustrated the functionality of the proposed design aid, and reference to module 'C' shows a skill concept package generating implied knowledge with respect to the total number of tolerance requirements per course of brickwork. Moore (1993b) suggested that a library of such packages could be developed, with one 'book' for each of the construction high level tasks. It is suggested that total tolerance requirements can be used, within a skill concept package, to forecast the time required for an operative of given skill to complete the placing of bricks forming a single course. However, the author does not propose that the forecast time should include any activity other than the actual placing;

levelling, etc. will be dealt with elsewhere in the ADA. The general theory supporting this proposal is discussed in more detail in section 6.3, but can be briefly summarised as a heuristic: the greater the number of tolerance requirements within a given area of product, the longer it will take to build. Total tolerance requirements are therefore suggested as an indicator of task difficulty.

**6.2.4 Module D: Buildability Assessment.** This module will be required to bring together the results of assessment by each skill concept package. The result will be a numerical value for the buildability of the design being assessed. Whilst this value, when viewed in isolation, may well be used to place the design portion at a particular point on a reference scale of absolutes ranging from poor to good buildability, this is not its primary function. Further research would be required to develop suitable reference points from which to produce such an absolute scale. The primary function of such a value at this stage of the research is to allow the comparison of an original form of a design with a revised form, and to do so in a manner which makes available relevant information at each stage of the analysis process. In doing this, the design aid will also contribute towards the user in the developing a level of expertise regarding buildability through simplification [Moore, Tunnicliffe (1994a)].

Further development of the proposed ADA may cause such a perspective to change, as supplementary understanding of how task difficulty impinges upon the production process is achieved. However, because of the present dearth of such understanding within the literature, the author suggests that without this

value there can be no meaningful comparison of buildability within different design solutions to a given problem. Facilitating the action of comparison between versions of a design solution is therefore suggested as initially being the most significant contribution the proposed ADA can hope to make to the presently existing buildability assessment problem.

### **6.3 Tolerance Requirements Theory.**

In processing CAD file data, module 'C' of the proposed ADA can be effectively seen as searching the data for members of a domain (buildability attributes). The author proposes that, as a means of progressing the development of a prototype ADA, the remainder of this programme of research will focus on the role of one attribute only: 'tolerance requirements', thereby concentrating development and testing on the finest level of problem decomposition achievable within the supporting theory. The attribute of 'tolerance requirements' role in the assessment of buildability will therefore be examined in further detail through consideration of an experimental approach.

Figure 48 illustrates two designs, 'A' and 'B', of a brick infill panel suitable for sealing up redundant window openings. A novice [Dreyfus & Dreyfus (1986)] designer may be of the opinion that panel 'B' is more difficult to construct than panel 'A', but may not be able to give valid, objective reasons for this. A number of common sense reasons can be put forward for such a perception: 'B' obviously uses more bricks than 'A'. This assertion is not, however, actually correct. Figure 49 shows that there are exactly the same number of bricks (totals of whole and cut bricks) in both cases.

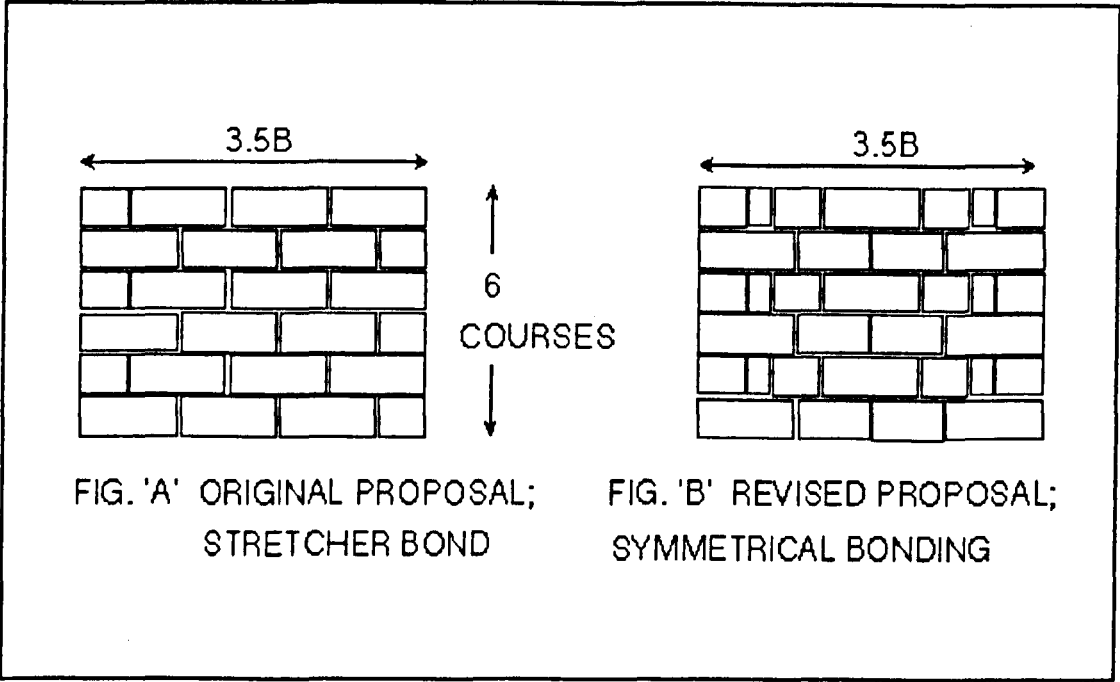


Figure 48. Experimental brickwork panels 'A' and 'B'.  
[Moore (1996d)]

### QUANTITIES: BRICK PANELS 'A' & 'B'

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	Full Bricks	3/4 Bricks	1/2 Bricks	1/4 Bricks	Bricks Used	No. of Perps
'A'	18	0	6	0	21B	18
'B'	9	6	12	6	21B	27

	Max. Perps in 1 course	Min. Perps in 1 course
'A'	3	3
'B'	6	3

Note: 'Perps' refers to the perpendicular, or vertical, joints between adjacent bricks.

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Figure 49. Comparative quantities for panel designs 'A' and 'B'.

There are, however, more cuts in design 'B' than there are in design 'A': perhaps a significant contributor towards the design being perceived as being



the more difficult. However, based upon the author's practical experience of bricklaying, the most difficult tasks generally seemed to involve the placing of the largest numbers of cut bricks within the smallest work space. It is possible to argue that such 'crowding' of the workspace, in terms of tolerance requirements, requires high levels of competence on the part of the operative. Without such competence locating and managing, in terms of projecting total requirements within the workspace, all of the imposed tolerance requirements would not be achievable. A link of this nature, between tolerances and competence, is generally implied within the training of construction operatives. Current NVQ bricklaying standards illustrate that as the student progresses, the tolerances which are deemed acceptable as evidence of achievement become less generous [CITB (1995)]. The intention being that the student moves towards being able to achieve industry standards consistently.

Industry standards were examined by Rankin (1982) in his work on quality control and tolerances for internal finishes in building. Rankin carried out measurements on fifty items in 125 new-build houses spread nationally over twenty sites. Using the resulting data, guideline and unacceptable work tolerances were established for a number of construction tasks. Figure 50 illustrates some of the tolerances established for openings in walls. Rankin noted that the easiest tolerances to define and assess were line, level and plumb, which are effectively the same functions as the extraction of 'X', 'Y', 'Z' co-ordinate data previously proposed within the functionality of the prototype design aid.

ITEM	BUILDER GUIDELINE TOLERANCE (median)	UNACCEPTABLE WORK TOLERANCE
A. Width of reveal	3mm in full height	8mm in full height
B. Level of reveal soffit	1mm in 1.0m	5mm in 1.0m
C. Plumb of reveal	2mm in 1.0m	7mm in 1.0m

Figure 50. Tolerances for openings in walls.  
[Summarised from Rankin (1982)]

However, the consideration of tolerances regarding level, line and plumb is not the whole answer to the problem of assessing task difficulty. This is exemplified by considering a single course of bricks within the panel designs 'A' and 'B'. The second course above ground level will suffice.

In panel 'A' there are three vertical joints in the second course. The operative has to place those joints within the restrictions of the overall length allowed for the course of brickwork, and the length of bricks being used: even the relevant British Standard (BS 3921) allows a random element to brick dimensions [Smith (1987)]. There is a limited scope to deal with such random variations by adjusting the width of the vertical joints between bricks; a possibility limited by the tolerances applicable to joint width: minimum and maximum joint widths will determine the tolerance applicable to the normal joint width (10mm). This usage of the term 'tolerances' should not be confused with the intended usage of the term 'tolerance requirements', as proposed by the author:

Tolerance requirements - *The defining of a given productive action in terms of*

*predetermined plumb, level, and square quality criteria. These criteria to be expressed in terms of x, y, and z co-ordinates.*

Applying this usage to the brickwork bonding in panel 'B', there are six vertical joints in the second course. The author suggests that the task of completing the course has now become more difficult with regard to the application of tolerance requirements, in that the accuracy requirement has effectively increased. The general theory (proposed by the author) predicts that in such a situation the rapidity component of skill would be reduced: an operative of given expertise will respond to increasing accuracy requirements by producing at a slower rate. This suggestion is based upon the work reviewed in chapter five, particularly the work of McRuer and Krendal. By increasing the number of vertical joints within a single course of brickwork of a given length the manual tracking element of task completion has become more complex. Given that the course is only 3.5 bricks long, the above problems are not insurmountable. However, the manner in which an operative deals with problems related to tolerance requirements is suggested by the author as being an exhibition of ability with regard to the accuracy component of skill.

**6.3.1 Initial Evaluation of General Tolerance Requirement Theory.** The initial evaluation will be undertaken through the comparison of two designs: panel 'A' and panel 'B' (see Figure 48), each requiring the same construction high level task: bricklaying. The designs will be compared for level of buildability as indicated by tolerance requirement theory, which should identify one design as being the more difficult to build. This can then be checked, at

a basic level, by actually constructing the two designs. Assuming certain constants can be achieved, such as consistent quality of materials and labour, the more difficult design should take longest to build: increased accuracy = reduced rapidity. As a proposal for further research, a number of different designs should be evaluated in this manner in order to check each of the proposed attributes utilised by the ADA for consistency.

There is no intention within this thesis to develop a full range of skill models; the intention is purely to test the hypothesis that such models are both possible to construct and relevant to the assessment of buildability.

In selecting a high level task (HLT) for evaluation, the main criterion is that of objectivity. The selected task must be one which operates on the basis of predominantly objective rules. This requirement follows the philosophy expressed by Pateman (1992) in connection with achieving Total Quality Management (TQM): "... if you can not measure it do not include it...". The prototype ADA will therefore only cover **one** HLT; bricklaying, suggested for three reasons:

1. It operates on the basis of a well developed and extensive set of objective rules, many of which relate to relationships between spatial co-ordinates in the use of a single component. The component itself is largely standard sized, with the exception of a number of defined standard special shapes.
2. There is the possibility of testing the projected assessment of brickwork design's buildability against the actual buildability achieved, by constructing the designed artifact.
3. The author trained as a bricklayer and so claims some expertise.

In making this selection there is no intention to suggest that bricklaying is an area of particular concern regarding buildability. Selection is solely on the basis of the above considerations. The initial evaluation of tolerance requirement theory through experiment, is discussed in chapter seven.

6.3.2 *RWL, JSI, etc.* In chapter five it was suggested that a number of existing approaches to the assessment of difficulty may have a role to play in the development of the proposed ADA. The main approaches were: job severity index (JSI); recommended weight limit (RWL); manual tracking considerations. Having developed the thesis further, it is now suggested the following responses are appropriate to the above approaches:

1. JSI - the suggested use of JSI multipliers does not appear to present significant benefit to the functionality of the prototype ADA at this point.
2. RWL - the movement control function within RWL may prove to be of relevance. This will be considered further in the light of completed experimental work (see chapter 7).
3. Manual Tracking research - the experimental work in chapter 7 aims to determine the relevance of manual tracking to skill modelling.

Other considerations are:

4. Gilbreth's 5th/6th Dimensions for assessing skill - within the context of the prototype ADA as developed thus far, the author does not perceive any requirement to investigate this possibility further.
5. Systems Theory - development work to this point does not indicate any significant benefit arising from the application of systems theory within the prototype, single HLT, design aid. However, systems theory may provide a vocabulary for the process of utilising more than one HLT within later versions of the design aid.

#### 6.4 Conclusion.

The intended end product has been identified, development proposals made and an evaluation method outlined. The innovative nature of the ADA and development proposals have also been discussed. Particular reference has been made to the problems of using expert systems for both the design and buildability problems. An alternative approach; development of an ADA utilising four modules based on the generic task philosophy, has been proposed.

- \* The extent of the proposed research has been shown in that only one high level task skill concept package will be produced as a prototype to test the operation of the proposed ADA.
- \* The above skill concept package is to be developed only within the context of the skill components of accuracy and rapidity.
- \* The response of the skill components of accuracy and rapidity to the buildability attribute of 'tolerance requirements' will be the means for evaluating the general theory of tolerance requirements.
- \* The above responses will be monitored during completion of panel designs 'A' and 'B'.
- \* It is **not** proposed to develop a full range of high level task skill concept packages. Such further development would be undertaken outside the boundaries of this programme of research (see: further research).

## **7. DETAILED DEVELOPMENT AND EVALUATION OF THE THEORY SUPPORTING THE PROTOTYPE ADA: Experiment No.1.**

*Note it is necessary that the machine should arrive at the same conclusions as the expert when it is given a problem to solve, but it is not necessary that the system should emulate the exact behaviour of the expert..*

[Firlej, Hellens (1991)]

This chapter deals with experimental testing of proposals regarding the role of the buildability attribute of tolerance requirements. Tolerance requirements has a role as both a generic task and as part of a skill concept package. A method proposed by the author for investigating these roles in the proposed buildability assessment process will be described, and the data resulting from the investigation method evaluated.

### **7.1 Investigation of 'Tolerance requirements' General Theory.**

Tolerance requirements have been suggested as being an important factor within the concept of buildability assessment proposed by the author. Emphasis will therefore be placed upon investigating the relevance of the tolerance requirements attribute to the functionality of the prototype ADA. On the basis of there being insufficient data within the sketch design to offer any significant increase in the design aid's level of functionality, the author proposes that problem decomposition beyond the level of buildability attributes will not be undertaken within this programme of research.

The experimental phase of this research operated within certain resource constraints, particularly given the practical nature of the experiments involving

Southfields College (Leicester) brickwork staff and students. The main constraints are summarised in figure 51, with the most significant constraint suggested as being that of student availability.

ITEM No.	NATURE OF RESOURCE RELATED CONSTRAINT
1.	Student availability, in that participation in the experiments was only available to those students who were ahead of schedule with their NVQ assessments. This limited the sample size.
2.	Student ability, which was governed by which students were available.
3.	Space available, as within a workshop environment there is usually little in the way of unused floor space. Consequently, the experiment models had to have a small footprint.
4.	Time available for each experiment, due to a need to ensure that students did not fall behind schedule on their NVQ assessments.

Figure 51. Resource related constraints on experiment methodology.

The small sample of students participating in the experiment is may be seen as a concern with regard to possible production variations commonly held attributable to the Hawthorne effect. The Hawthorne studies were carried out by Elton Mayo from 1927 to 1939 at Western Electric Hawthorne works. Over this period five different experiments were carried out and irrespective of the changes made in working environment the participating workers increased production; a result attributed to the fact that the workers were responding positively to the stimulus of someone paying them special attention, otherwise known as the Hawthorne effect. This has dogged human performance researchers ever since, particularly with regard to the supposed need for control groups so as to identify the extent of the Hawthorne effect on those workers



who know they are being observed. It is worth noting that in the original studies carried out by Mayo the second series of tests, involving the use of a control group, resulted in both the control group and the experimental group increasing their performance to almost the same extent [Bailey (1982)].

There are three key considerations with regard to the nature of the Hawthorne effect in general:

- i) can occur in any experimental work.
- ii) invariably experimental performance is better than real world performance.
- iii) does not mean that the data has no real world significance for productivity.

[Singleton, Fox, Whitfield (1971)]

A further important consideration is that the effect is primarily of concern in situations where an improved method of working is being designed and evaluated. Within the experimental work in this thesis the objective is not to produce a better method of working for the operative, but to seek to provide a mechanism which alerts design process workers when their designs start to approach the limits of achievable construction within the existing method of carrying out construction processes, such as bricklaying. On this basis any productivity gains during the construction phase will result from achieving a task difficulty responsive design process which avoids the problem of imposing difficult to construct structures on the construction process. This research does not therefore concern itself with the productivity of the construction method.

Rather it seeks to determine:

- i) if any objective relationship between the demands of the 'as drawn' design and the response of the construction process, at the task level, can be identified.

- ii) the basis and nature of such a relationship.

Given these intentions, the case can be argued that the Hawthorne effect, which will inevitably occur in the experimental work, is not detrimental to the resulting data, and therefore no steps, such as the inclusion of a control group, need to be taken to explicitly identify the extent of it. This argument is further based on the following:

- i) the Hawthorne effect always results in improved performance, ie the rate of work becomes faster.
- ii) the real world performance is always slower than the experimental performance.
- iii) within such slower performance any cause-and-effect relationship will exist, as it did in the experimental work, but its effect will be manifest more slowly. Within the experimental work in this thesis, the intention is to establish if a possible cause (task difficulty) and a possible effect (reduced rate of production) are closely related in some manner. Such an approach is the essence of a good human performance study [Bailey (1982)].
- iv) the Hawthorne effect is particularly important when tests are being carried out to evaluate job design decisions. The experimental work in this thesis does not involve testing of this nature; it is effectively a study and for this reason alone the Hawthorne effect is of less significance to this research [Bailey (1982)].
- v) experiments of a time study nature are usually carried out to identify an improved method of work, and then provide data for the purposes of forecasting actual rates of work, bonus scheme calculations, etc. Within such end uses, the Hawthorne effect is obviously an important consideration. The proposed design aid, however, is not intended for such uses.

The above points are particularly relevant within the context of highly controlled experimental work where exact sampling theory is used. In such cases large samples of a given population are not required, with sample sizes of less than

thirty being applicable [Spiegel (1961)]. Within exact sampling theory the use of Student's 't' statistic enables determination of any statistically significant association between two variables. In the event of such an association the data can be accepted as reliable, in which case it would be expected, with a reasonable level of confidence, that the results could be repeated with a larger sample of the population [Bailey (1982)].

A further consideration in the argument for not considering the Hawthorne effect is that if the data gathered can be shown not to exhibit autocorrelation then any omitted explanatory variables (from the regression equation describing the relationship between identified variables) can be deemed to have no significant impact on the robustness of the regression equation [Lewis-Beck (1993)]. Autocorrelation can be identified by using the Durbin-Watson test provided that the data being analysed contains 15 or more observations. The minimum number of observations within the experimental work is 24, and therefore the Durbin-Watson test can be utilised to identify any problems with autocorrelation within any regression equations produced from the data gathered.

A final consideration is that study design techniques can be used to identify the minimum required number of observations which will result in robust relationships being identified [Wilson, Corlett (1995)]. One such technique, which can be used as a preliminary means of identifying data needs, is activity sampling. Given the required level of accuracy for a presumed relationship between two factors within a given study of work, and the percentage of cause attributable to the independent factor, it is possible to identify the number of

observations of a single model required by a study to establish if the presumed relationship actually exists. The equation

$$N = \frac{4(1-p)}{S^2p}$$

[Heap (1987)]

Where  $p$  = required attributable level, and  $S$  = range of accuracy required, will identify the number of observations ( $N$ ) required. Given that this research seeks to achieve a level of accuracy at least equal to current MTM levels ( $\pm 20\%$ ) the attributable level  $p$  is determined as being 80%. On this basis the required number of observations is 25 per model.

A second equation can be used to verify the above value for  $N$ . The equation -

$$N = \left[ \frac{t(SD)}{(M1-M2)} \right]^2$$

Where  $t$  = critical value of  $t$  statistic,  $SD$  = standard deviation,  $M1$  = mean for data set 1, and  $M2$  = mean for data set 2, is derived from the equation -

$$t = \frac{(M1 - M2)N^{1/2}}{SD}$$

[Wilson, Corlett (1995)]

and can be used to calculate the number of observations required when comparing two sets of data, such as times for panels 'A' and 'B' for one student. The equation is recognised as presenting difficulties in establishing the required level of performance in advance of carrying out an initial study, particularly with regard to the standard deviation value as it is unlikely that similar studies will have been carried out previously. In these circumstances, many ergonomists use their expertise and guess [Wilson, Corlett (1995)]. The author accepted the following values, resulting from a general literature search,

on the basis of the study being an iterative process of establishing realistic standards in a new area of research -

$t$  at a 5% level of significance =  $\geq 1.717$ ;  $M1 - M2 = \leq 0.01$ ;  $SD = \leq 0.04$ .

The above values give a value of  $N = 48$  for comparative analysis between two sets of data (24 observations per set). The indication therefore is that a number of observations approximately equal to 25 will give sufficiently robust results within the context of a tightly controlled study of the presumed relationship between task difficulty and time taken. Given all the above points, the author suggests that this study can proceed without further consideration of the Hawthorne effect or the need to put in place a control group.

A further consideration regarding the sample is that students, rather than fully skilled bricklayers were used. Given the current financial situation being faced by the construction industry, construction firms are not generally supportive of research which they have not initiated themselves. Obtaining experienced bricklayers for the experimental work would therefore have proved difficult. More important, however, is that experienced bricklayers were not seen as being required at this stage of the research, due to the emphasis placed on manual tracking research in the development of the investigative experiment. It was decided that students of varying expertise, ranging from novice to near-expert, would more clearly demonstrate how the development of expertise (skill) affected manual tracking abilities. The use of student bricklayers was therefore seen as less of a problem than sample size.

7.2 Tolerance requirements: experiment no. 1.

Experiment 1 utilised the brickwork panels discussed previously (Figure 48), and which are suggested as having the benefits listed in Figure 52 with respect to isolating effects resulting from varying tolerance requirements. A possible disbenefit of using the panels was that their similarities may result in a student gaining sufficient relevant expertise on panel 'A' to improve their performance on panel 'B'. Knowledge transfer of this type is referred to as being either positive or negative transfer [Poulton (1974)]. The argument for the existence of positive knowledge transfer within the experiments can be largely countered by consideration of the following points, and Figure 53:

BENEFIT	NATURE OF BENEFIT
Constant overall dimensions	Panels of equal dimensions, shape and overall area ( <u>perimeter</u> X, Y, Z co-ordinates are equal). There should therefore be no variation, detrimental or beneficial, in operative work performance which can be argued to result from differing dimensions etc.
Elimination of technical aids other than level and tape	Panels are not sufficiently large to allow operatives the opportunity of setting up corners and using a line. Tolerances have to be judged initially through the operatives ability to process visual data such as the bed thickness on each course.
One source of varying TR.	Panels only vary with respect to bonding requirements. These bonding requirements will be the only source of varying tolerance requirements (TR).

Figure 52. Suggested benefits of using designs as illustrated in Figure 48.

- (i) students selected for the experiment were of an expertise level which should allow them to complete panel 'A' without any 'new' learning taking place;
- (ii) Panel 'B' is suggested as representing a manual tracking task of greater complexity than panel 'A' due to the greater number of x,y,z co-ordinates occurring within the perimeter of the panel.

	NUMBER OF INTERNAL X, Y, Z CO-ORDINATES.
<b>PANEL 'A'</b>	72. (3 joints / course, 4 co-ordinates / joint)
<b>PANEL 'B'</b>	108 (50% greater than panel 'A' due to 3 courses having 6 joints / course)

Figure 53. Comparison of panels 'A' and 'B' internal X, Y, Z co-ordinates.

A further consideration is that all models used within this experimental work were developed in consultation with experienced brickwork staff at Southfields College (Leicester) so as to enable testing of the presumed relationship between task difficulty and time taken without the introduction of new knowledge to the participating students. Consequently, all models used are similar to existing models used within the NVQ assessment framework. The reduction / elimination of positive knowledge transfer is suggested as being important given the previous comments regarding manual tracking abilities and student expertise. Panel 'B' therefore presents an opportunity for the students to exhibit their ability in transferring rules regarding acceptable brickwork tolerances to a situation which can be argued to require a higher level of planning skills, or ability to 'project' probable outcomes on the basis of present knowledge (see chapter 5), than panel 'A'. However, it is worth noting that construction work is invariably prototype in nature, and that any task will represent, at some level, the opportunity to further develop expertise. Given that the intention within this research is to identify any characteristics of construction work which could form the basis of a generic assessment tool for buildability at the task level, such opportunities to develop further individual expertise are suggested as not being problematic. This is particularly so given the controlled nature of the experiments.

7.2.1 Experiment Factors and Controls.            A number of study techniques are possible within the experimental paradigm, each of which have their particular advantages and disadvantages which can be summarised under the headings given in Figure 54.

	CRITERIA			
TECHNIQUE	Reactivity	Face Validity	Control	Measure- ment Detail
Task Analysis	zero	high	-	-
Observation/ Record	low	high	zero	low
Questionnaire/ Ratings	medium	medium	low	medium
Experiments	high	low	high	high

Figure 54. Comparison of experiment techniques by different criteria [Wilson, Corlett (1995)]

Whilst the experimental technique generally has disadvantages regarding face validity and reactivity, these can be overcome to some extent through the careful selection of the measure(s) to be used in the experiment. The experimental technique also has the advantages of allowing high factor control and level of measurement detail, both of which can not be achieved by any other recognised technique. Given the need to achieve a high level of measurement detail, the experimental technique is the only one viable for this research, and therefore identification of all factors which could affect the identified dependent variable - time taken - is required as follows;



TASK	'R'	OPERATOR	'R'	TOOLS	'R'	ENVIRON -MENT	'R'
Materials	3	Age	1	Defective Level	4	Noise	4
Method	4	Gender	3	Trowel	4	Light	3
Size	3	Experience	1			Heat	3
Shape	3	Dexterity	1			Space	3
Location	3	Visual Acuity	3				
Time Allowed	n/a	Health	3				
		Size	3				
		Strength	5				
		Mental State	5				
<b>Response Key</b>	1	Build in at multiple levels.	3	Fix at a single level.	5	Ignore	
	2	Treat as co- variate.	4	Random -ise	n/a	not applicable	

Figure 55. Factors affecting dependent variable and control response 'R'

The measure selected within the experiment was time taken, validated on the basis of:

1. validity; experimental work to support construct validity.
2. reliability; using split-half reliability generally  $\geq 0.8$  is desirable. (panel 'A' results give split-half values of approximately 2.0).
3. sensitivity; reacts sufficiently well to changes in independent variable to allow easy measurement.

[Kerlinger (1986)]

A final consideration in the selection of the measure to be used concerns the speed-accuracy trade-off (SATO) phenomenon which occurs in resource limited tasks (the more time of effort expended, the more accurate the results) such as brickwork. In such cases one of three alternatives with regard to the

selection of the measurement scheme must be implemented:

1. Fix speed and measure accuracy.
2. Fix accuracy and measure speed.
3. Let speed and accuracy be chosen by the operator and sort out the effects during analysis.

[Wilson, Corlett (1995)]

With regard to this research the alternative selected is to fix accuracy (within standard NVQ criteria) and measure speed. An important consideration is that perfect accuracy is not required, as this leads into diminishing returns considerations.

A final factor is that of subject selection, with a key consideration being that of human variability, and how to obtain reliable results despite it. Three students were used, with each student being taken as a representative of the following groups within the bricklaying population; < 1 year of experience, >1 but <2 years of experience, >2 but <3 years of experience. Two key approaches are to consider both inter-subject (between subjects) variability and intra-subject (within one subject) variability. The general argument laid out previously regarding the controlled nature of the experiments, combined with the statistical techniques used to analyse the results considers many of the point related to inter/intra subject variability. However, when using exact sampling approaches an unavoidable disadvantage is a resultant lack of generality in the findings; in this case the findings can not be taken as indicators of performance outside each of the three experience categories identified. This is suggested as not being a significant disadvantage given the original nature of the research, and is discussed further in section 7.2.2. The experiments used in this research are of an intra-subject design, due to the manner in which subjects (students) were

assigned (same-subject).

The first experiment required each of the two students student to complete panel 'A' and then, after a short break, complete panel 'B'. Before commencing each of the panels the students were asked to complete a brief questionnaire which required them to outline the extent of their bricklaying experience (student 1 had <1 year of experience, student 2 had <2 years of experience); their perception of each panel's difficulty, and their intended approach (strategy) for the completion of each panel. This information was of relevance in identifying any difference of strategy and perception of difficulty with changing levels of experience/expertise. No difference in perception of difficulty was noted between both students. Interestingly, both students described the same general strategy prior to commencing panel 'A', and both also proceeded to use a different strategy when actually constructing the panel (see video recording: appendix six). Completed questionnaires for panel 'A' are included as appendix seven. The panels were assessed against typical NVQ level 2 tolerances by the students brickwork lecturer. Video equipment was used by the author to record the students work on both panels, and the work performance of each student was also timed, using a time-study stopwatch. The student's frequency of use of their level on each course was also noted. Experiment 1 results are presented in Table 1.

**7.2.2 Experiment Results.** The results indicate varying work performance rates on each course of panel 'A'. Given that the tolerance requirements are effectively the same on each course of panel 'A', general TR theory would

	PANEL 'A'				PANEL 'B'			
STUDENT 1.	TIME PER COURSE (1-6) IN STD. MINS.	VARIATION % (+/-) OVER 1st COURSE	TIMES LEVEL USED	VARIATION % (+/-) OVER 1st COURSE	TIME PER COURSE (1-6) IN STD. MINS.	VARIATION % (+/-) OVER 1st COURSE	TIMES LEVEL USED	VARIATION % (+/-) OVER 1st COURSE
Course 1	3.19		5		5.17		10	
2	3.44	+7.84	8	+60.00	8.54	+65.18	12	+20.00
3	4.89	+53.29	8	+60.00	6.77	+30.95	15	+50.00
4	4.18	+31.03	9	+80.00	7.90	+52.80	12	+20.00
5	5.21	+63.32	11	+120.00	6.09	+17.79	13	+30.00
6	3.64	+14.11	8	+60.00	4.86	-6.00	9	-10.00
TOTALS	<u>24.55</u>	Range=55.48	<u>49</u>	Range=60.00	<u>38.52</u>	Range=71.18	<u>71</u>	Range=60.00
STUDENT 2.								
Course 1	1.80		3		1.73		4	
2	2.16	+20.00	6	+100	4.66	+169.36	9	+125.00
3	2.80	+55.55	8	+167	3.29	+90.17	8	+100.00
4	2.34	+30.00	6	+100	4.39	+153.76	7	+75.00
5	2.61	+45.00	8	+167	3.77	+117.92	10	+150.00
6	2.54	+41.11	8	+167	4.43	+156.07	14	+250.00
TOTALS	<u>14.25</u>	Range=35.55	<u>39</u>	Range=67.00	<u>22.27</u>	Range=79.19	<u>52</u>	Range=175.00

Table 1. Experiment No. 1: Results

predict that each course would take a similar amount of time to complete. The result being a small, or even zero, variation in the time taken for each of courses 2-6 over that taken for course 1. Examination of column three in Table 1 shows that this is not the case. The smallest variation is +7.84%, whilst the largest is +63.32%: both values being achieved by the same student. This indicates that the original perception of tolerance requirements may have been in error, and there was some variation in tolerance requirements taking place, causing production times to vary over each course of panel 'A'.

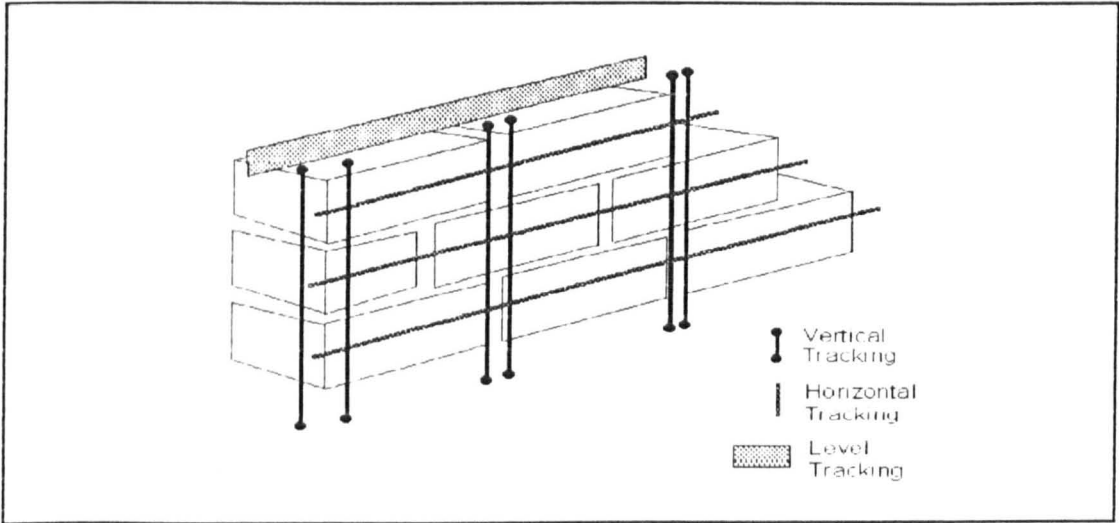


Figure 56. Suggested relationships forming manual tracking standards for satisfactory completion of brickwork.

The suggestion (by the author) that bricklaying be regarded as a manual tracking task offers a possible explanation for the disparity in panel 'A' results. Within a manual tracking task there are standards which the participant is trying to achieve. Brickwork standards are in the form of a relationship between a given brick and other bricks in the same course, and also the preceding course(s), if any. Such standards have long been implied, if not explicitly

stated, within the rules governing the achievement of satisfactory brickwork [Adams (1913)]. Figure 56 illustrates a suggestion for the nature of the relationships forming manual tracking standards for brickwork tasks. To achieve these tracking standards, monitoring of the brickwork has to be carried out as the work proceeds, thereby slowing the work rate if the student does not have sufficient expertise to carry out monitoring and placing as part of one process. Unproductive time is therefore being created when the student interrupts the laying of bricks to explicitly monitor the completed work's standards.

A component of the recorded student times will be unproductive time utilised for the explicit monitoring of tolerance requirements, and no other behaviour which could be classed as productive. Examination of the video recording for experiment 1 produced data on explicit monitoring time, relevant to each course, for both students on each panel. These times were subtracted from the original data (see Table 1), to give values for productive (as opposed to production) time. The resultant times, and revised variation values, are presented in figure 57. The data in Figure 57 show the effect of explicit monitoring on time taken to complete each course. By extracting explicit monitoring time from the overall production time, the resultant revised productive time per course can be examined. As one example, the revised panel 'A' productive times on courses 2-6 for student 2 vary, in comparison to course 1, to a reduced extent (compared to Table 1 results) across a range of 28.36%; a reduction of 22.22% in variation on the unadjusted total times per course. The revised variation for student 1 of 57.26% represents a slight increase of 3.21%.

	PANEL 'A'			PANEL 'B'		
STUDENT 1.	MONITOR- ING TIME (STD. MIN)	PRODUC- TIVE TIME PER COURSE	REVISED VARIAT -ION (%)	MONITOR- ING TIME (STD. MIN)	PRODUC -TIVE TIME / COURSE	REVISED VARIAT -ION (%)
Course 1	0.64	2.55		2.32	2.85	
2	1.99	1.45	-43.14	2.80	5.74	+101.40
3	2.27	2.62	+2.74	3.57	3.20	+12.28
4	2.10	2.08	-22.60	2.10	5.80	+103.51
5	2.30	2.91	+14.12	3.15	2.94	+5.00
6	1.56	2.08	-22.60	1.86	3.0	+5.26
TOTALS	<u>10.86</u>	2.12 Avge.	Variation range = 57.26%	<u>15.80</u>	3.92 Avge.	Variation range = 98.51%
STUDENT 2.	Variation range = 1.66 std. mins.			Change % over panel 'A' = + 31.26	Change % panel 'A' = +84.91	
Course 1	0.46	1.34		0.29	1.44	
2	0.75	1.41	+5.22	1.20	3.46	+140.28
3	1.25	1.55	+15.67	1.51	1.78	+23.61
4	0.72	1.62	+20.90	1.86	2.53	+75.69
5	1.23	1.38	+2.99	1.93	1.84	+40.00
6	1.30	1.24	-7.46	2.32	2.11	+46.53
TOTALS	<u>5.71</u>	1.42 Avge.	Variation range = 28.36%	<u>9.11</u>	2.19 Avge.	Variation range = 100.28%
	47.42% less than student 1. Variation range = 0.84%	33.0% faster than student 1		Change % over panel 'A' = +59.54	Change % over panel 'A' = +54.22	

Figure 57. Panel 'A' and 'B' results from Table 1: experiment No. 1, revised to allow for explicit monitoring time.

A further consideration for the general TR theory can be identified in the

simplistic (involves no consideration of tolerance requirements) assumption that, because courses 2, 4 and 6 in panel 'B' contain 2.33 more units of brick than in panel 'A', each course will take 2.33 times longer to produce. However, the times for these courses in panel 'B' are not consistently greater than those of panel 'A' by a factor of 2.33. Table 1 data shows that the overall trend for both students is for the time taken per course to drop over courses 2, 4 and 6. This trend suggests that the simplistic approach to considering production times as being merely a reflection of the quantity of production involved does not hold true, and that a more complex relationship between task difficulty and production time is involved.

Panel 'B' also presents a less clear picture with regard to the effect of explicit monitoring than is the case with panel 'A'. Student 2, for example, completed course 1 of panel 'B' using less monitoring time than on course 1 of panel 'A'. Student 2 exhibits a bricklaying technique which results in the rapid completion of the first course; course 1 on both panels was completed more rapidly than any other course, with or without the effect of explicit monitoring time being considered. This has a distorting effect on the percentage variation values for subsequent courses in that they are calculated with reference to course 1.

The rapid times of Student 2 appear to be achieved primarily through not engaging in significant levels of explicit monitoring. The explicit monitoring time for course 1 on panel 'B' is fully 75.83% less than the second lowest time for explicit monitoring on the panel (course 2). After taking into account explicit monitoring time, productive time for student 2 has a maximum variation over



course 1 on panel 'B' of +140.28%. Production time for student 2 on panel 'B' had a maximum variation of +169.36%. By dealing with productive time and monitoring time separately, the range of variation which the prototype ADA will have to deal with is beneficially reduced. However, the author attempted a number of approaches to reduce further the distorting effect of one individual's bricklaying technique. These approaches focused on discerning the role of monitoring within the production process.

Prior to making any attempts at reduction of distortion within the results, they were used to produce a forecast of monitoring and productive times. These times were for a student (student 3) of a higher level of expertise (>2 years but <3 years of experience; approaching NVQ Level 3) in completing panel 'A'. In this manner a basic evaluation of the premise that increasing expertise levels and reducing work times exist in a 'lock-step' relationship can be carried out. By forecasting monitoring and productive times for student 3 on the basis of the incremental change in performance from student 1 to student 2, a broad feel for the relationship between expertise and production may be obtained. This is of relevance to the proposed design aid's intended use of skill concept packages.

Forecasting of times was carried out by use of a basic spreadsheet model (see disk: appendix eight). A detailed discussion of the work carried out by student 3 can be found in chapter 8, where experiment 2 is dealt with. However, at this point there is a value in comparing the actual times achieved by student 3 to the times forecast by the undeveloped basic model of performance.

<b>Student 1 Monitoring Time (Std. mins)</b>	<b>Student 2 Monitoring Time (Std. mins)</b>	<b>Forecast Student 3 Monitoring Time (Std. mins)</b>	<b>Actual Student 3 Monitoring Time (Std. mins) &amp; % error of forecast time</b>
0.64	0.46	0.33	0.32 (+3.12%)
1.99	0.75	0.28	0.65 (-56.92%)
2.27	1.25	0.69	0.97 (-28.86%)
2.10	0.72	0.25	0.72 (-65.28%)
2.30	1.23	0.66	0.45 (+46.67%)
1.56	1.30	1.08	1.03 (+4.85%)
<b>Student 1 Productive Time (Std. mins)</b>	<b>Student 2 Productive Time (Std. mins)</b>	<b>Forecast Student 3 Productive Time (Std. mins)</b>	<b>Actual Student 3 Productive Time (Std. mins) &amp; % error of forecast time</b>
2.55	1.34	0.70	1.57 (-63.69%)
1.45	1.41	1.37	1.60 (-14.38%)
2.62	1.55	0.92	1.71 (-46.20%)
2.08	1.62	1.26	1.47 (-14.29%)
2.91	1.38	0.65	1.41 (-53.90%)
2.08	1.24	0.74	1.39 (-46.76%)

Figure 58. Forecast times (on basis of 'distorted' data) v. actual monitoring (unadjusted), and productive times for student 3: panel 'A'.

Figure 58 data suggests that the model is not good at forecasting monitoring times in general: an error range of 103.59%, with a maximum error of -65.28%. It does, however, achieve low levels of error on courses 1 and 6. The situation regarding productive time forecasting is better: an error range of 49.40%, and a maximum error of -63.69%. The significance of these error ranges should be considered in terms of:

1. their relevance to the 'lock-step' premise discussed previously. It is suggested that error ranges of the magnitude shown in

Figure 58 indicate a relationship between expertise (in perception of task difficulty) and production times of greater complexity than that contained within the above premise.

2. the total error ranges deemed acceptable by other forecasting techniques. For MTM techniques, for example, acceptable levels of analysis accuracy are at best + or - 20%, giving a total error range of 40% [Konz (1995)]. Total error for student 3 forecast monitoring time is 111.95%, and total error range for forecast productive time is 63.69%.

These points provided an initial focus for the distortion reduction exercise.

It is important to reiterate at this point that this research intends only to test the feasibility of a prototype ADA which attempts to model, rather than precisely replicate, those skills relevant to particular operative high level tasks. There will therefore be no significant weakness in developing the prototype on the basis of formulaic representations which closely represent, rather than precisely replicate, operative skill. This research seeks only to develop a formulaic representation closely approximating to operative skill in *responding to varying tolerance requirements* within the high level task of bricklaying. The key consideration is suggested as being the student's perception of difficulty in relation to varying TR values.

### **7.3 Panel 'A' distortion reduction: method 1.**

Method 1 focused on reducing distortion in the monitoring times. The starting point being a consideration of what represents an ideal figure for the use of the bricklayer's level: the argument being that use of a level beyond this figure would represent a squandering of possible productive time, whilst use below this figure would represent a possible reduction in product quality.

Consideration by the author of the tracking requirements discussed previously, combined with an evaluation of how plumb, level and square may be best achieved with minimum use of the level, resulted in the following values: course 1, four instances of level use; course 2, six instances; courses 3 - 6 inclusive, eight instances. Monitoring times for each course were adjusted on the basis of average time per instance of level use for students 1 and 2, which was added or subtracted as required from the actual monitoring times achieved. The resultant times were then used to forecast student 3 adjusted monitoring times.

Adjusted monitoring times occupied an error range (and total error) of 96.35%: a 6.81% decrease over the unadjusted times, indicating that adjusting monitoring times for students 1 and 2 only was not significantly beneficial with regard to reducing distortion in the experiment results. However, adjusted forecast monitoring times for student 3 were being compared to unadjusted actual monitoring times for that student. Actual monitoring times for student 3 were adjusted to represent times which would have been achieved, had the student used the level for the ideal number of instances, in order to treat both sides of the comparison equally. Adjusting actual monitoring times for student 3 reduces the total error range to 20.31%. The adjusted monitoring time values for students 1, 2 and 3 were then subjected to regression analysis to determine their predictive value, which was determined at an R-sq adjusted value of 99.3% for the regression equation of:

*Student 3 Monitoring Time = 0.178 + 0.302(Student 1 adjusted monitoring time) + 0.20(Student 2 adjusted monitoring time).*

There are two problems concerning the above regression equation:

1. This equation can forecast adjusted monitoring time only on the basis of previously recorded monitoring times which have been adjusted for the number of times the level should be used per course.
2. Adjustment of the above type is imposing an ideal method upon one aspect of the construction process.

However, the forecast times for student 3 using this regression equation occupied a total error range of 4.6%, with the largest single error being on course 2 (+2.5%). The author therefore suggests that, given the above identified problems, an acceptable level of accuracy has been shown to be achievable on one component of the previously discussed formulaic representation of skill: explicit monitoring time in relation to the number of times the level should be used per course. This component can only be of value in the assessment of buildability if an ideal manner of explicit monitoring, rather than a variable actual manner, can be accepted. Within the context of comparing two versions of a given design, the use of such an ideal is suggested as not being unduly problematic. However, within the context of forecasting production times for use in programming construction work, such a manner would be unacceptable.

#### **7.4 Panel 'A' distortion reduction: method 2.**

Method 2 considered distortion within the recorded productive times. Because explicit monitoring within the experiment was recorded separately from productive time, no distortion within the overall production time could be attributed to varying usage of the level. Other factors which were determined

by the author as not having any definable relationship to distortion with respect to production times on panel 'A' were: brick cutting, the number and size of cut bricks being consistent throughout all courses of panel 'A'; pointing of joints, no pointing being required.

An aspect of tolerance requirements not covered by explicit monitoring, for which the term *tacit monitoring* is proposed by the author, was then considered. Tacit monitoring, as recognised by this research, does not present itself as an interruption of the production process and is therefore not explicitly measured. Whilst the precise nature of any interaction between tacit monitoring and rate of production lies outside the scope of this programme of research (see: Further Research), it is possible to consider the general nature of such an interaction within the context of the accuracy component of skill.

Tacit monitoring is suggested (by the author) as being a possible generic task existing within the umbrella of Krendal and McRuer's work on manual tracking. Within this context, tacit monitoring can be argued to involve monitoring the work in progress against work completed, and a projection (mental model) by the operative of work to be done, in terms of x,y,z co-ordinate data, hence the proposed relationship with the accuracy component of skill. Figure 60 illustrates an initial suggestion for tolerance requirements on selected bricks within panel 'A'. Total tolerance requirements per course, which are calculated on the basis of the logic illustrated in Figure 58, for panel 'A' are identified in Figure 61.

The author wishes to make clear at this point that the buildability attribute of

'tolerance requirements' takes a different perspective on the construction process to that represented by the term 'tolerances'.

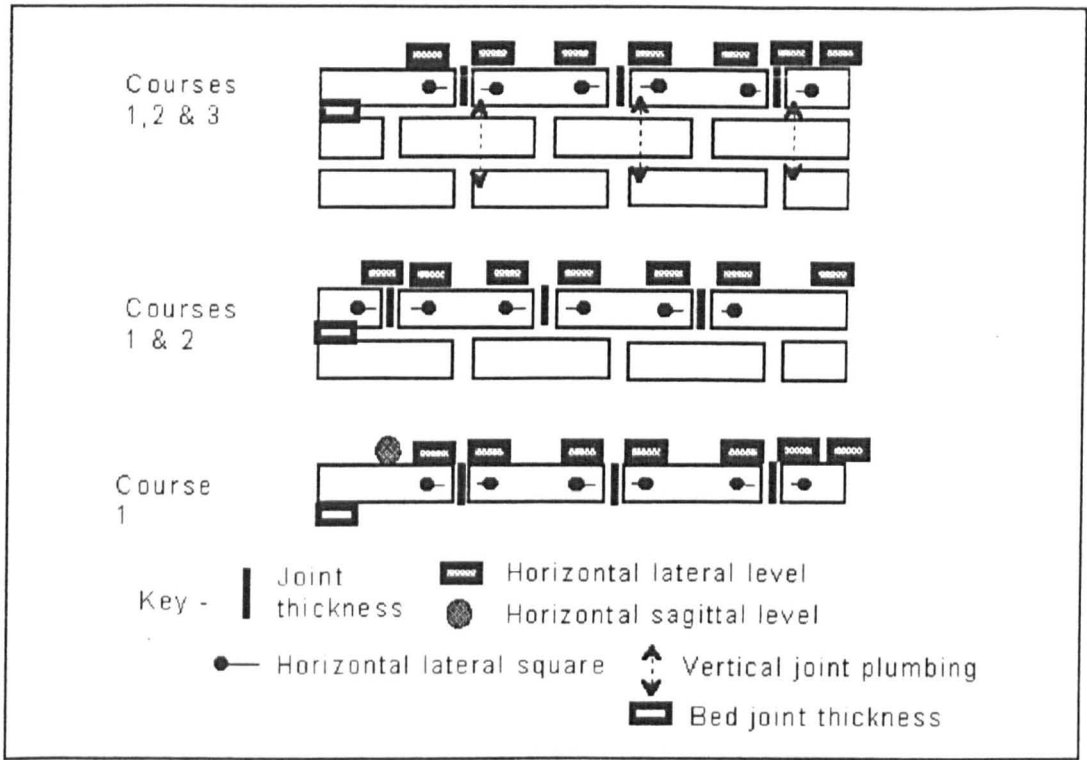


Figure 59. Examples of suggested Tolerance Requirements: panel 'A'.

Course.	Relevant Tolerance Requirements and number of occurrences eg. (2)	Total Requirements
No. 1	Horizontal lateral level [HLL] (4), Horizontal sagittal level [HSL] (8), Vertical joint thickness [VJT] (3), Horizontal joint thickness [HJT] (1), Horizontal lateral square [HLS] (8), Sagittal plumb [SP] (2)	26
No. 2	As course 1 (26) plus: SP (2), HLS (2)	30
No. 3	As course 2 (3) plus: Vertical joint plumb [VJP] (4)	34
No. 4+	As course 3, plus: Lateral ranging [LR] (2)	36

Figure 60. Total tolerance requirements per course: panel 'A'.

Within the context of this research, 'tolerance requirements' does not involve any consideration of acceptable tolerances normally encountered within the construction process. In effect, there are zero tolerances within 'tolerance requirements': the operative is assumed to be striving for zero defects, irrespective of the quality of work actually achieved on site. The proposed design aid therefore builds up its own 'mental map' of the artefact to be produced based on zero tolerances. Given the scale of design detail typically produced at sketch design stage (1:100) there appears to be no logical argument for considering acceptable levels of error (tolerances), which may be at the level of  $\pm 1\text{mm}$ , within the proposed design aid.

*7.4.1 Acquiring the target.* The initial stage of testing the data regarding student productive time and total tolerance requirements per course was to carry out a regression analysis. The intention being to test the strength of any relationship which may exist between the two factors as the basis of a tool for forecasting student productive time on the basis of tolerance requirements. Evidence of a strong relationship between the factors would indicate a means of assessing task difficulty on an objective basis; tolerance requirements. Regression analysis produced an equation of the relationship between the two factors of:

$$\text{Student 2 Productive Time} = -0.308 - 0.0237(\text{Student 1 Pt}) + 0.0157(\text{TR}).$$

$$\begin{array}{ccc} & (-1.132) & (-0.39) & (5.92) \end{array}$$

$R^2 = 62.9\%$ ;  $\bar{R}^2 = 59.3\%$ ; DW = 1.92

This model was reasonably accurate regarding a statistically significant link between tolerance requirement and student 2 productive times ( $t = 1.717$ ).



There is also no evidence of autocorrelation ( $DW = 1.45$ ). There is, however no statistically significant connection between student 2 placing time and the constant. In order to improve upon this accuracy, the author examined ways in which the tacit monitoring element could be extracted from productive time data, and assessed in terms of time (standard minutes). The reasoning behind this approach was that if tolerance requirements do slow down the rate of production, the most obvious source of that slow down would be increased levels of tacit, rather than explicit, monitoring. This required searching the literature domain of cognitive psychology, with particular reference to information processing by operatives carrying out manual tracking tasks.

Information processing research suggested that in manual tracking tasks a key consideration is the need for the operative's eyes to be looking directly at the target, or object, so that the brain can acquire the required detail about it [Poulton (1974)]. This is particularly important regarding the role of stepped tracking in the development of expertise in manual tasks such as bricklaying. The differing levels of student performance are suggested by the author as possibly being an example of the relationship between expertise and stepped tracking. Stepped tracking occurs when an operative chooses to make large movements, say between a stack of bricks and the wall under construction, at high speed prior to slowing as the target, the point at which the brick is to be located in the wall, is approached. This behaviour results from the operative learning through experience that tracking at a constant speed between start and finish points of a movement results in high levels of placing inaccuracy, or acquiring of the target, resulting in repetitive corrective action. This is

especially so when the target is small, as illustrated by Craik's ratio rule and Fitt's ratio rule [Poulton (1974)]. Both indicate that large quick movements have an error, roughly proportional to their size, at an average of 5%. An error of 5% within a movement covering a distance of 600mm would result in a placement error of approximately 30mm. Given that brickwork joint sizes are typically 10mm in width, a placement error of 30mm would not be acceptable.

A further indication of the importance for placing accuracy in detail work can be found in design recommendations for screen displays, which suggest a minimum visual angle of approximately 15 min. of arc in good lighting conditions. This equates to an object of 4.3 mm in diameter, or approximately half the width of a brickwork joint, viewed from a distance of 1m [Downton (1991)]. Acquiring of the target therefore appears to be an important aspect of skill.

*7.4.2 Information transfer.* Placing accuracy is also dependant upon information processing, or transfer, in that the operative is constantly searching the visual workspace for information which aids in acquiring the target. The use of long, fast movements requires less information about the workspace than the use of short, slow movements: information transfer during short, slow movements takes place at a higher rate than on long, fast movements. Small to medium scale tasks can be examined for information transfer rates through the use of software packages such as Designer v3.52. This package was developed for the purpose of applying NIOSH guidelines to the designing of tasks involving hand-arm movements. This software has the facility to calculate

information transfer rate, or bits, per move. Figure 61 [Designer (1996)] illustrates that long movements proportionately require less information transfer than short movements.

Distance of Move		Target Width		bits/move
(mm)	(inch)	(mm)	(inch)	
700.00	27.56	10.00	0.39	7.1
10.00	0.39	2.00	0.08	3.3
		Total		<u>10.40</u>

Figure 61. Bits/move values for typical bricklaying movements.

Whilst the generalisation that increased information transfer requirements will slow the rate at which a task can be performed holds true, there is also a secondary consideration of cascade processing. Cascade processing occurs when one action does not have to be completed before information processing for the next action can commence [Eysenck (1994)]. The author suggests that, within the activity of information transfer, the effect of cascade processing on movement time would simply be too complex a matter for the proposed ADA to deal with precisely. The point that this research does not intend to accurately mimic every nuance of skill, either explicit or tacit, possessed by an operative, must be restated. Rather, the model of skill adopted for the prototype ADA would achieve an appropriate level of accuracy by decomposing a task only so far as is required to model stepped tracking. A benefit of such a simplified approach to skill modelling is that it allows the proposed design aid sufficient flexibility to deal with possible future outcomes from the current discussions on an industrialised construction industry. Such a future industry

will rely heavily on prefabrication, which has implications for the training of operatives; what skill(s) will they actually require? Whilst such questions cannot be answered fully at this point, the general approach suggests that buildability attributes such as 'interfacing' will increase in importance [Neale, Price, Sher (1993)]. 'Interfacing' has implications for 'tolerance requirements', therefore by using 'tolerance requirements' as a basis of buildability assessment a degree of 'future-proofing' for the proposed design aid against changes in desirable skill outcomes for operatives appears to be offered.

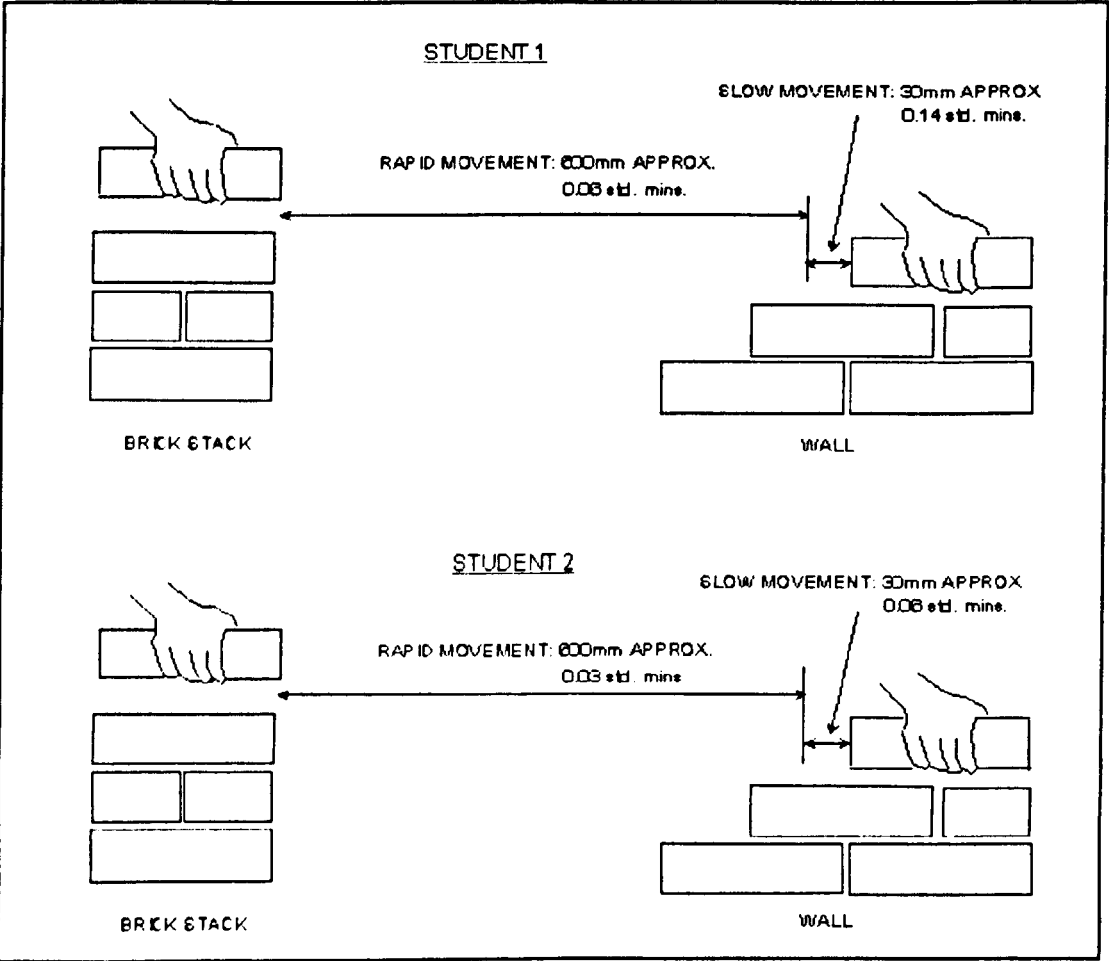


Figure 62. Sample time / distance data (students 1 and 2; panel 'A') as evidence of stepped tracking.

Examination of the video recording for students 1 and 2 showed evidence of stepped tracking occurring, as shown in Figure 62. This resulted in detailed retiming of the video to determine how much time each student spent on tracking movements, and how much on *placing movement* (defined by the author in terms of time spent locating a component within a subassembly).

Course	Brick	Student 1 Times		Student 2 Times		Tolerance Req'ment (per brick)
		Tracking (Tt)	Placing (Pt)	Tracking (Tt)	Placing (Pt)	
1	1	0.06	0.14	0.03	0.05	7
	2	0.04	0.20 em	0.04	0.06 em	6
	3	0.05	0.11 em	0.03	0.06	6
	4	0.04	0.17 em	0.04	0.09 em	8
2	1	0.05	0.12	0.08	0.10 em	8
	2	0.09	0.11	0.07	0.07	7
	3	0.09	0.10 em	0.07	0.06 em	7
	4	0.12	0.27 em	0.11	0.12 em	9
3	1	0.03	0.18	0.03	0.13 em	9
	2	0.06	0.22	0.06	0.08	8
	3	0.04	0.12 em	0.05	0.08 em	8
	4	0.06	0.19 em	0.03	0.12 em	10
4	1	0.04	0.23	0.05	0.13 em	10
	2	0.08	0.23	0.08	0.10	8
	3	0.08	0.21 em	0.11	0.07 em	8
	4	0.11	0.08 em	0.07	0.14 em	10
5	1	0.04	0.26	0.04	0.11 em	10
	2	0.10	0.21	0.03	0.09	8
	3	0.07	0.31 em	0.03	0.08 em	8
	4	0.05	0.19 em	0.03	0.13 em	10
6	1	0.04	0.18	0.05	0.12 em	10
	2	0.08	0.21	0.09	0.09	8
	3	0.07	0.18 em	0.08	0.09 em	8
	4	0.14	0.12 em	0.06	0.14 em	10
		Pt Average = 0.176 Ptem Av'ge = 0.161		Pt Average = 0.072 Ptem Av'ge = 0.091		

Figure 63. Tracking and placing times for students 1 and 2: panel 'A'.

Times for tracking and placing movements per brick for students 1 and 2 on each course of panel 'A', along with the tolerance requirements for each brick, are supplied in Figure 63. All times are in standard minutes (std. mins.). The suffix 'em' against a placing time indicates that it was followed by an explicit monitoring action: the use of the level. It can be argued that a placing movement which is followed by an explicit monitoring action may be less precise, and therefore faster, than one which is not to be validated by explicit monitoring. However, the average figures for placing times by do not identify such a pattern: student 1 has an average for placing times followed by explicit monitoring which is less than that for unmonitored placing times. Student 2 times represent the converse situation. The author found no clearly identifiable causal factors, and concluded that there may be aspects of personality at work, which are manifested in terms of error shock for student 1 in particular. Error shock is normally considered as occurring at the macro scale in econometric analysis, such as when underestimated funding requirements affect subsequent consumption decisions, for example [Cassidy (1981)]. There may well be an argument for considering error shock at the micro level in that an operative who is overly concerned about the possibility of making errors will possibly perceive a significant risk of error to exist in all parts of the task. The consequence of this could be a lack of focus on the truly difficult aspects of the task with a resultant lack of response to them. This possibility was examined further whilst carrying out regression analysis on the placing time data for students 1 and 2 and the tolerance requirements per brick on panel 'A'.

#### 7.4.3 *Placing times and tolerance requirements.*      The data for tracking and

placing times, along with the tolerance requirements, was tested for the strength of any relationships between the three factors through a stepwise regression. Tolerance requirements and the placing times for student 2 demonstrated the strongest relationship with a t-ratio value of 11.04 (a ratio of  $\geq 1.717$  indicates a statistically significant relationship at a 95% level of confidence). Prior to examining this relationship specifically, the data for placing times and tolerance requirements for each student was placed through a regression analysis to provide a base equation and R-sq.adjusted ( ) value for evaluation of subsequent equations. The resultant equations and analysis data were:

1. Student 1 Pt = 0.147 + 0.0040(TR).  $R^2 = 0.0\%$ ;  $R^2 = 3.1\%$ ;  $t = 0.47$ ;  
(1.49) (0.84) DW = 2.03.
2. Student 2 Pt = -0.0449 + 0.0167(TR).  $R^2 = 77.1\%$ ;  $R^2 = 78.1\%$ ;  
(-3.21) (8.87)  $t = 11.94$ ; DW = 2.01.

suggests that error shock may be the cause for the lack of statistical significance in the relationship between placing time and tolerance requirements. The student 1 equation can not therefore be used as the basis of predicting the response of students within this group to tolerance requirements.

Student 2 data exhibits a statistically significant relationship between the two variables, with no evidence of autocorrelation. The resultant equation suggests that students within this group see tolerance requirements (either explicitly or implicitly) as accounting for approximately 77% of the possible causes of task difficulty. This student 2 equation was accepted as a suitable basis upon which to develop the general theory of tolerance requirements further.

A matter of particular importance to the general theory, and thereby the functionality of the proposed design aid, is the matter of identifying and counting tolerance requirements. Within the literature no definitive guidance was located as to how tolerance requirements should be identified and/or counted in any given circumstances. A number of different approaches to identifying and counting tolerance requirements (TR) were attempted. Each approach was constrained by the requirement that TR must be definable in terms of x,y,z co-ordinates, in order that they can be located within a CAD workspace. Within this constraint the author identified a minimum count of three TR per brick using one approach, and a maximum of eleven per brick using a different approach. This variation, when used for regression analysis, resulted in a best R-sq.adj. value of 77.1% and a worst R-sq. value of 43.9%.



STEP No.	ACTIONS REQUIRED (Artifact 1: panel 'A')
1.	Take wall thickness, 'z', ÷ by brick length (mm), classify wall as brick multiple: $102.5 \div 215 = 0.5$ brick wall. Record.
2.	Take wall length, 'x', ÷ by brick length, record number of bricks (3.65), subtract whole bricks from total ( $3.65 - 3 = 0.65$ ), convert part brick to mm (139), subtract number of whole bricks x 10mm ( $3 \times 10 = 30$ ) from part brick ( $139 - 30 = 109$ ), classify to nearest multiple of brick (0.5b), sum whole and multiple for total per course = 3.5b
3.	Record number of vertical joints; total bricks / course - 1, or multiple ( $3.65 - 0.65 = 3$ )
4.	Take wall height, 'y', ÷ by brick height (65mm), record no. of courses (6.9), subtract whole bricks from total ( $6.9 - 6 = 0.9$ ), convert part brick to mm (58.5), subtract no. of whole bricks x 10mm (60) for number of bed joints, classify remainder to nearest multiple of brick (0), record no. of courses (6)
5.	Record total number of bricks in wall (21)
6.	Take course 1, go to brick 1, define tolerance requirements (TR) as: 'x' axis, (0); 'y' axis, 1 (HLL-see Fig. 60), 1 (BJT), 1+1 (HSL); 'z' axis, 1+1 (HLS), 1 (SP) sum TR for brick 1 = 7. Go to brick 2, take brick 1 value, subtract 1 (BJT), subtract 1 (SP), add 1 (VJT), sum TR for brick 2 = 6. Repeat until last brick, take brick 2 value, add 1 (SP), sum TR for brick = 7. Sum TR for course = 26.
7.	Take course 2, go to brick 1, define TR as: course 1, brick 1, add 1(SP); sum TR for brick 1 = 8. Go to brick 2, take brick 1 TR value, subtract 1 (SP), subtract 1 (BJT), add 1 (LP), sum TR for brick 2 = 7. Repeat until end of bricks on course 2. For final brick add 1(SP), sum TR for course = 30
8.	Take course 3, repeat TR actions per brick as course 1, add 1 per brick (VJP), Sum TR for course = 34
9.	Take course 4, repeat defining actions per brick as course 3, take brick 1, add 1 (lateral ranging), take end brick, add 1 (lateral ranging), sum TR for course = 36.
10.	Repeat until all courses assessed
11.	Tabulate TR values / brick / course

Figure 64. Tolerance requirement calculation algorithm (Version 1).

Small differences in the tolerance requirement count for individual bricks were found to have a significant effect on the resultant R-sq. value. In order to ensure consistency the author produced the algorithm at Figure 64, based on the logic for TR illustrated previously, to determine the TR count per brick. The algorithm will function within the proposed design aid structure after groupsets of explicit information, for each artifact category within panel 'A', have been produced by module 'B' of the proposed design aid (Fig. 45). The equation:  $\text{Student 2 Pt} = -0.0449 + 0.0167(\text{TR})$  is accepted as the basis of further developing the accuracy component of skill modelling. This will be done initially by predicting placing times for panel design 'B', with its greater variety of tolerance requirements. In the event that predicted placing times have an acceptable level of error, the research will have shown that a possible basis (the effect of tacit monitoring, in the form of slower placing movements as a response to increasing TR values) for the assessment of task difficulty in designs, prior to construction, has been identified. Such a basis is similar in philosophy to that supporting the work of Raouf et al discussed in chapter five, but differs in structure and execution.

Prior to examining the results for panel 'B' in more detail, the author wishes to make clear that there is no intention at this point of implying any positive or negative value to either explicit or tacit monitoring. Both simply exist within a relationship linking them to task difficulty, as expressed in terms of tolerance requirements only at present, and rate of production. Such a relationship is in line with the general trend of the theory proposed by the author regarding assessment of task difficulty.

### 7.5 Panel 'B' data.

Results from the panel 'B' component of experiment 1 (see Figure 65) indicate that this panel was more difficult to construct than panel 'A'. Courses 2, 4 and 6 had, with one exception, longer production times than courses 1, 3 and 5, which were similar, in terms of tolerance requirements, to the equivalent courses in panel 'A'. Such a pattern would be expected from application of the general TR theory. The simplistic argument that courses 2, 4 and 6 have longer production times on panel 'B' solely because there are more units of brick per course than in panel 'A' (7 compared to 4) has been discussed previously, but will be returned to here to further illustrate the development of expertise.

A simplistic argument of 75% increase in brick units resulting in a 75% increase in production time allows examination of panel 'B' production times for the actual increase, or decrease, over panel 'A' times, as illustrated in Figure 65. The actual change in production time only falls within the 75% increase allowed by the above argument on two occasions. These occasions (course 6 for each student), should be considered in terms of the learning curve for panel 'B': both students have decreasing production times over courses 2, 4 and 6. Under such circumstances, the increase in production time would eventually fall below the 75% value. Of greater importance is the fact that the increase in production time exceeded 75% by a sufficiently large margin on courses 2 and 4 to suggest the simplistic argument is not wholly relevant to actual production situations.

Course	Brick	Student 1 Times		Student 2 Times		Tolerance Requirement (Total)
		Tracking (Tt)	Placing (Pt)	Tracking (Tt)	Placing (Pt)	
1	1	0.10	0.10	0.06	0.06em	7
	2	0.11	0.21em	0.05	0.06	6
	3	0.18	0.23em	0.06	0.06em	6
	4	0.08	0.09em	0.03	0.06em	7 (26)
2	1	0.10	0.21em	0.06	0.09em	8
	2	0.13	0.07em	0.11	0.11	7
	3	0.20	0.19em	0.04	0.08	7
	4	0.10	0.17em	0.05	0.10em	7
	5	0.14	0.14em	0.06	0.08em	7
	6	0.12	0.15	0.06	0.07	7
	7	0.10	0.09em	0.05	0.09em	8 (51)
3	1	0.11	0.25em	0.06	0.12em	9
	2	0.20	0.22em	0.07	0.10em	8
	3	0.11	0.17em	0.09	0.09em	8
	4	0.14	0.15em	0.07	0.15em	9 (34)
4.	1	0.14	0.27em	0.04	0.11	10
	2	0.08	0.22	0.09	0.10	8
	3	0.09	0.24	0.08	0.10	8
	4	0.06	0.07em	0.07	0.09em	8
	5	0.10	0.15	0.08	0.14	8
	6	0.07	0.24	0.09	0.08	8
	7	0.11	0.14em	0.10	0.14em	10 (60)
5.	1	Student 2 data discontinued: Rsq.adj. = 0.0%; t=0.82; DW=2.45		*	0.18	10
	2			*	0.16	8
	3			*	0.20	8
	4			*	0.15	10 (36)

Figure 65 Tracking and placing times for students 1 and 2 on panel 'B'.  
[NOTE: 'em' denotes movement followed by explicit monitoring action]

PANEL 'A'		PANEL 'B'		
STUDENT 1	TIME / COURSE (STD. MINS) [+75% VALUE]	TIME / COURSE (STD. MINS)	INCREASE / DECREASE (STD. MINS)	INCREASE / DECREASE %
Course 1	3.19	5.17		62
2	3.44 [2.58]	8.54	5.10	148
3	4.89	6.77		38
4	4.18 [3.63]	7.90	3.72	89
5	5.21	6.09		17
6	3.64 [2.55]	4.86	1.22	34*
STUDENT 2				
Course 1	1.80	1.73		-4
2	2.16 [1.62]	4.66	2.50	116
3	2.80	3.29		18
4	2.34 [1.76]	4.39	2.05	88
5	2.61	3.77		44
6	2.54 [1.91]	4.43	1.89	74*

Figure 66. Percentage increase / decrease in production times: panel 'B'. (Star \* denotes value below the 75% increase suggested by simplistic reasoning)

A further point raised by the comparative data in Figure 66 is that the production times for courses 1, 3 and 5 are not equal on panels 'A' and 'B': all production times on panel 'B' for these courses, with the exception of student 2; course 1, are greater than on panel 'A' by a range of 17 - 62%. Both the simplistic argument of production time increasing proportionately to any increase in brick units, and the general theory proposed by the author, would be in agreement that courses 1, 3 and 5 on panels 'A' and 'B' should be completed in similar times. A regression analysis on the data for panel 'B' resulted in the following:

1. Student 1 Pt =  $-0.0953 + 0.0097(\text{TR})$ . Rsq.adj. = 0.00%; t = 0.82;  
DW = 2.45.
2. Student 2 Pt =  $-0.0550 + 0.020(\text{TR})$ . Rsq.adj. = 36.7%; t = 3.93;  
DW = 1.30.

There is no statistically significant relationship between placing time and tolerance requirements (t must be  $\geq 1.717$  for significance) and there is no auto correlation in the performance by student 1. Within student 2's performance there is a statistically significant relationship (t must be  $\geq 1.711$ ) but the Durbin Watson test statistic is at the lowest limit of the test inconclusive values (1.30), and the accuracy of the equation has dropped to 36.7%. This suggests that the nature of the tolerance requirement relationship has changed within panel 'B', perhaps regarding some aspect of the relationship between tolerance requirements on a number of bricks, rather than considering individual bricks in isolation, which the experimental work has thus far not highlighted. The general reasoning behind this suggestion is that the work regarding manual tracking tasks indicates that operatives construct a mental model of the work to be carried out. This allows the operative to plan actions forwards in time: such forward planning must consider any implications for work currently being carried out, of impending tolerance requirements.

Furthermore, a mental model such as is suggested here would be of value in using work which has been completed, possibly some considerable time previously, as a check by the operative for the accuracy of work in progress. On this basis, the

nature of any relationship between tolerance requirements and placing time could involve the operative in consideration not only of the tolerance requirements of work in progress, but also of work to come, and work already completed. The author proposes that such consideration of past, present and future work be referred to as *TR overflow*, and that there is a relationship between TR overflow and cascade processing. Detailed examination of such a relationship lies outside the scope of this thesis and is suggested as a possible area for further research. Preliminary examination of the relationship is carried out in connection with brickwork characteristics in chapter eight.

Figure 67 illustrates student 2 forecast placing times for panel 'B', which were produced using the equation discussed previously, along with actual placing times. Of the 26 bricks in the first five courses of panel 'B', the forecast times for 10 bricks exceed the target error range of  $\pm 20\%$ . The greatest error is  $-47.50\%$  for brick 3 on course 5. A number of possible reasons for the disparity between forecast and actual placing times were examined.

**7.5.1 Prediction accuracy of equation.** Student 2 placing times for a range of tolerance requirements within panel 'B' have been found, at a 95% confidence level of statistical significance, with an  $R_{sq.adj.}$  value of 36.7%. This represents a decrease from the  $R_{sq.adj.}$  value of 77.1% on panel 'A', thereby indicating a decrease in the prediction accuracy of the regression equation. The author problem(s) lying outside the proposed linkage between tolerance requirements and

	<u>Tolerances</u> <u>Per Brick</u>	<u>Total</u> <u>Per</u> <u>Course</u>	<u>Forecast</u> <u>Placing</u> <u>Time (std. mins)</u>	<u>Total</u> <u>Per</u> <u>Course</u> <u>(std. mins)</u>	<u>Actual</u> <u>Placing</u> <u>Time</u> <u>(std. mins)</u>	<u>Error:</u> <u>Forecast</u> <u>v. Actual</u> <u>(std. mins)</u>	<u>Error:</u> <u>%age</u>
Course 1	7		0.0850		0.06	0.025	41.667
	6		0.0650		0.06	-0.005	-7.143
	6		0.0650		0.06	-0.005	-7.143
	7	<u>26</u>	0.0850	<u>0.27</u>	0.06	0.025	41.667
Course 2	8		0.1050		0.09	0.015	16.667
	7		0.0850		0.11	-0.055	-39.286
	7		0.0850		0.08	0.005	6.250
	7		0.0850		0.10	-0.015	-15.000
	7		0.0850		0.08	0.005	6.250
	7		0.0850		0.07	0.015	21.429
	8	<u>51</u>	0.1050	<u>0.55</u>	0.09	0.025	31.250
Course 3	9		0.1250		0.12	0.005	4.167
	8		0.1050		0.10	0.005	5.000
	8		0.1050		0.09	0.015	16.667
	9	<u>34</u>	0.1250	<u>0.40</u>	0.15	-0.025	-16.667
Course 4	10		0.1450		0.11	0.035	31.818
	8		0.1050		0.10	0.005	5.000
	8		0.1050		0.10	0.005	5.000
	8		0.1050		0.09	0.015	16.667
	8		0.1050		0.14	-0.045	-30.000
	8		0.1050		0.08	0.025	31.250
	10	<u>60</u>	0.1450	<u>0.69</u>	0.14	-0.005	3.571
Course 5	10		0.1450		0.18	-0.035	-19.444
	8		0.1050		0.16	-0.055	-34.375
	8		0.1050		0.20	-0.095	-47.500
	10	<u>36</u>	0.1450	<u>0.72</u>	0.15	-0.005	-3.333

NOTE 1: Forecast Placing Times calculated using: Forecast Placing Time =  $-0.0550 + 0.020(\text{Tolerance Requirements})$

Figure 67. Forecast placing times compared to actual placement times: student 2; panel 'B'.



suggests that this situation indicates one or more of the following problems lying outside the proposed linkage between tolerance requirements and: production placing time; an error in identifying and counting tolerance requirements; observer error in collecting tracking and placing time data.

**7.5.1.1 Possible Production Problems.** The author reviewed the video recording of Student 2 completing panel 'B'. Any interruptions to work in progress were noted, and the placing times around such interruptions checked to ensure that the author had not counted interruptions as part of the time data. The actual placing time for brick 3, course 4, resulted from explicit monitoring feedback; the student placed the brick incorrectly and relaid it in a more cautious manner. No additional interruptions, or other production problems, were identified during the review.

**7.5.1.2 Observer Error in Collecting Time Data.** Prediction errors recorded above a level of  $\pm 31.65\%$  (error range indicated by regression equation) caused particular concern, and the placing and tracking elements of the data for such bricks were retimed. Expertise requirements in using MTM techniques, etc. have been discussed previously, and it would seem a level of expertise is also required in the identification of placing movements in particular. The difficulty lies in deciding when a placing movement stops and normal productive movements recommence. This is especially problematic given the short duration (typically 0.05 to 0.10 std. mins.) of placing movement. Relatively small observer errors can result in large differences between forecast and actual tracking times.

In order to guide future observers in the recording of placing time movements, the original concept of placing time requires to be more closely delineated:

*Placing Time* - measured from a point approximately 5% of the travel distance away from the final location of the component being placed, to a point at which the placing movement can be reasonably stated as having been replaced by normal productive movements.

No significant timing errors were identified, thereby suggesting that the disparity between forecast and actual placing times were, to some extent, attributable to changing TR values.

7.5.2 *Identifying and counting tolerance requirements.* The results on the panel 'B' model indicated that tolerance requirements (TR) theory needed further development to more accurately reflect the circumstances encountered by an operative. As a 'what if' exercise, the author utilised the spreadsheet produced for calculating placing time errors to produce an ideal set of TR for panel 'B' by simply altering the TR value for each brick with a placing error of  $\pm 20\%$  until the error fell below  $\pm 20\%$ . The exercise results were examined to see if the optimised TR values could be logically arrived at within the context of the original TR algorithm.

STEP No.	ACTIONS REQUIRED (Artifact 2: panel 'B')
1 to 9 inc.	As per algorithm version 1
10	<b>Course 5: take course 4, repeat TR defining actions per brick. Take brick 1, subtract 1 (LR), add 1 extra (SP); take brick 2, add 1 extra (LP), add 1 extra (BJT); repeat until penultimate brick; take final brick, repeat TR defining actions for brick 1. Sum TR for course = 60</b>

Figure 68. Tolerance requirement calculation algorithm (version 2).

Of the TR values under consideration, seven had changed in the 'what if?' exercise. The author was unable to establish a logical basis upon which the TR values for bricks one and four (TR = 6) of course one, and brick two of course two (TR = 9) could be determined. In the remaining instances TR values equal to the optimal values could be established, and these values resulted in the following regression equation:

$$\text{Forecast Placing Time} = -0.0991 + 0.0253(\text{TR}). \quad R^2 = \overline{71.40\%}; R^2 = 70.20\% \\ (-3.69) \quad (7.74) \quad t = 7.74; DW = 2.37.$$

This equation illustrates that a statistically significant relationship between placing time and TR values has been identified, and that there is no autocorrelation in the data ( $DW > 1.46$ ). Whilst the level of correlation within the data is acceptable from the viewpoint of forecasting placing times for student 2, the equation does not explain 29.80% of possible factors affecting operative performance. The TR algorithm was then revised by the author (see Figure 68). Those actions revised from version 1 of the algorithm are boldened.

## 7.6 Conclusions

A number of conclusions can be drawn from the research covered in this chapter:

- \* Tolerance requirements have been shown to be a potential basis for the assessment of task difficulty within the context of brickwork as a high level task.
- \* The manner in which tolerance requirements are identified and counted has a significant effect upon the accuracy of forecast placing times. This research has developed an algorithm for the tasks of identification and counting tolerance requirements.

- \* Observing and timing actual placing times has been shown to be an activity within which observer expertise is important. This research has produced a definition of that which constitutes a placing movement as a basis for guiding potential observers.
- \* Whilst this research has shown that information transfer rates on small, slow movements, such as placing movement, decrease, there is no conclusive evidence that the forecasting of placing times requires a level of information input equivalent to that required by a RWL approach to assessment.
- \* A formulaic representation capable of forecasting placing times as a response to TR values within a given brickwork design has been developed by this research.

The conclusions should be considered in terms of the author's proposals for the assessment of task difficulty, as an indicator of buildability, on the basis of the low levels of information available at the sketch design stage. Research thus far has indicated a possible means of developing an automated design aid of the type proposed by the author. Chapter eight will further test and develop the formulaic representation of operative response to tolerance requirements produced by this research.

The author suggests that the research thus far has indicated a possible need for a change of perception by designers from seeing the demand situation as less of a compilation of equally relevant parts, and more as a complete whole within which only some parts are of relevance to buildability.

## 8. DETAILED DEVELOPMENT, TESTING AND EVALUATION OF THE THEORY SUPPORTING THE PROTOTYPE ADA: Experiment No. 2.

*All behaviour can be said to involve decision and action.*

[Bilodeau, Bilodeau (1969).]

Chapter seven investigated the effects of increasing tolerance requirements on two brickwork tasks of an essentially two dimensional nature: panels 'A' and 'B' contained no changes of direction and students 1 and 2 were working parallel to their frontal axis only. Experiment no. 1 allowed the development of a predictive equation (for student 2 only) for placing time of an individual brick on the basis of its tolerance requirements. The equation was developed within the context of the two dimensional tasks represented by panels 'A' and 'B'. Experiment no. 2 was designed to investigate the effects on the accuracy of the predictive equation, if any, of carrying out a brickwork task of a three dimensional nature.

A particular aspect of skill to be investigated through the use of a three dimensional task is the suggestion [Welford (1976)] that the higher levels of crafts skills are concerned with the translation mechanism, whereby decisions are made as to what should be done under particular circumstances. Higher level skills therefore depend on the ability to decide which tasks require to be executed, and are more akin to intellectual skills argued to relate to ideas and principles; skill is therefore not a constant in that it responds to production 'environment' changes. The three dimensional task represented by model 2 in experiment number two is argued to represent a series of production 'environment' changes.

8.1 Tolerance requirements: experiment no. 2.

Experiment no. 2 was undertaken by one student and comprised two stages. Stage 1 required the student (student 3) to complete panel 'A', which was intended to act as a control in giving a common element for assessing the performance of the three students (see Figure 57). The data indicates the effect of student 3's greater expertise through explicit monitoring times which are consistently lower than those achieved by student 2. A factor to consider in connection with data for student 3 is the construction technique used, which differed from that used by the other two students, as can be seen in the video (appendix 6). Overall, the performance of student 3 was similar to that of student 2, as illustrated in Figure 69, with the exception that student 3 achieved the required tolerances on panel 'A'. On this basis, any actual placing times for student 3 could be expected to be lower than forecast placing times.

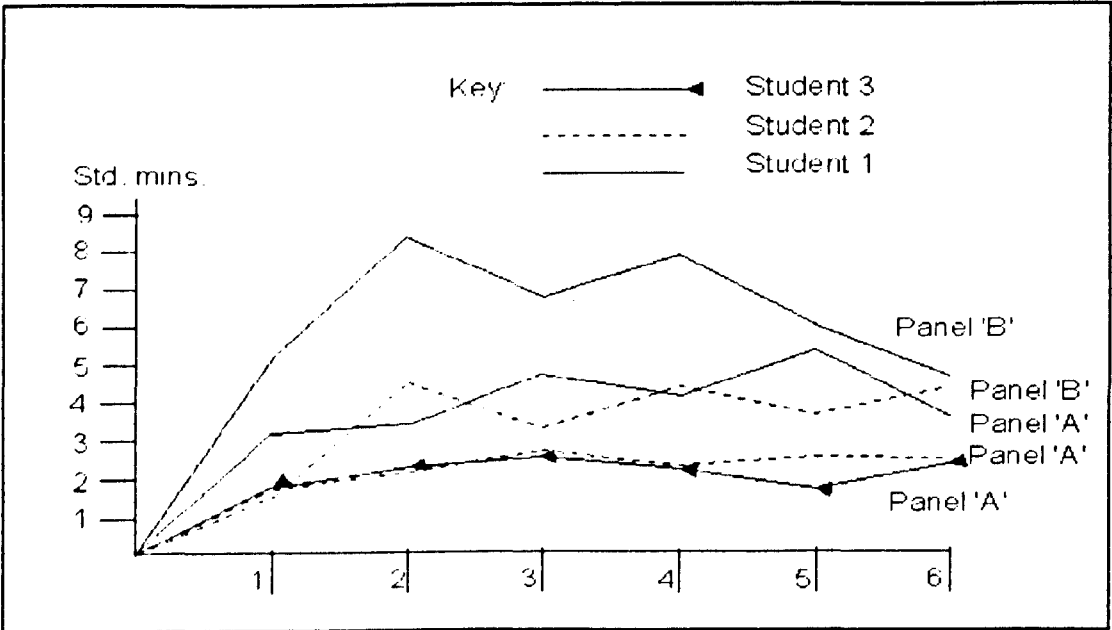


Figure 69. Performance data for students 1-3 on panels 'A' and 'B'.

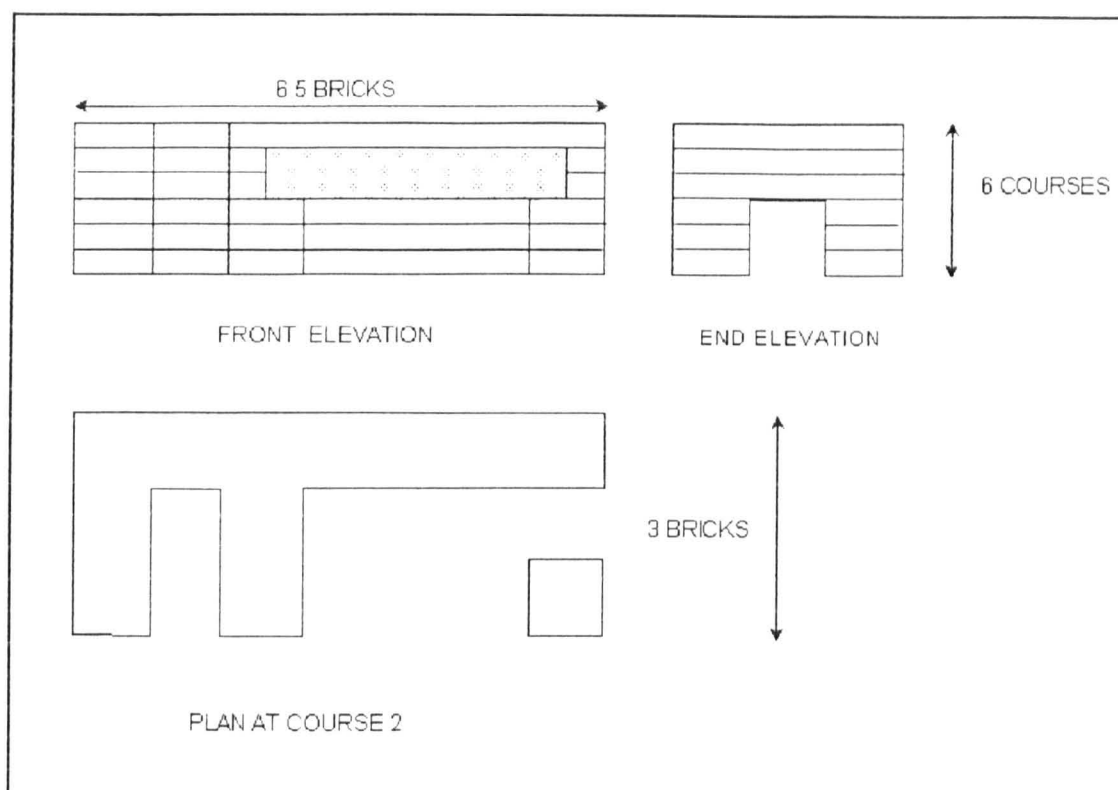


Figure 70. Experiment No.2: stage 2 task (model 2).

A consideration at this point is that regression analysis of data concerning the performance of student 3 on model 1; experiment 2 (Figure 70), resulted in a low level of correlation between placing times and tolerance requirements:

$$\text{Student 3 Pt} = 0.118 - 0.00215(\text{TR}); R^2 = 2.6\%; \bar{R}^2 = 0.00\% \\ (4.95) \quad (-0.77) \quad \text{DW} = 2.00$$

This result was initially of concern in that it indicated a considerable drop in correlation from the 70.2% achieved by student 2. Further examination suggested that the level of expertise possessed by student 3 engendered a casual approach to constructing what was rated by the student as an 'easy' model. In comparison model 2 was rated by the student as 'difficult but possible'. Viewing of the video shows student 3 paying less attention to his actions on model 1 than was the case with student 2. Student 3 is therefore

argued not to be responding solely to the matter of tolerance requirements. This is supported by comparison of the mean, standard deviation and placing time range values for all three students on panel 'A', as shown in Figure 71.

	Student 1	Student 2	Student 3
Mean Placing Time	0.180	0.097	0.010
Standard Deviation	0.059	0.026	0.017
Placing Time Range	0.23	0.08	0.07

Figure 71. Mean, Standard Deviation, Range values: Panel 'A'; all students

It can be seen that student 3 is slightly slower than student 2, but is more consistent whilst also recording less explicit monitoring time. The author suggests this effect is a resultant of increased expertise and can be referred to as *expertise certitude*. The unfortunate aspect of expertise certitude is that data affected by it cannot be seen as a natural response to tolerance requirements. It is therefore proposed that the regression equation resulting from data recorded for student 2 on panel 'B' be used for forecasting placing times by student 3 on model 2.

Stage 2 of experiment no. 2 involved the construction of the model illustrated in Figure 70 (model 2), which was designed to investigate the effects on student performance of those task characteristics stated in Figure 72. The anticipation being that the increased perception of difficulty for this model by student 3 would reduce the effect on time data of the expertise certitude previously discussed. Resultant data can therefore be argued to more accurately respond to tolerance requirements.



No.	NATURE OF CHARACTERISTIC
1.	Requires work to be carried out in three dimensions.
2.	Requires work to be carried out within a confined space.
3.	Requires use of projecting ability to relate otherwise isolated work to the main structure.

Figure 72. Characteristics of stage 2 task shown in Figure 70.

These characteristics were identified by the author as being relevant to the further development of the forecasting equation on the basis of their possible overspill effect (see chapter 7) regarding tolerance requirements, and as examples of a changing production 'environment'. The model for stage 2 avoided complex bonding requirements, with the majority of the model utilising full bricks, as this characteristic was investigated by experiment no. 1, and so as to isolate any overspill effect resulting from the identified characteristics.

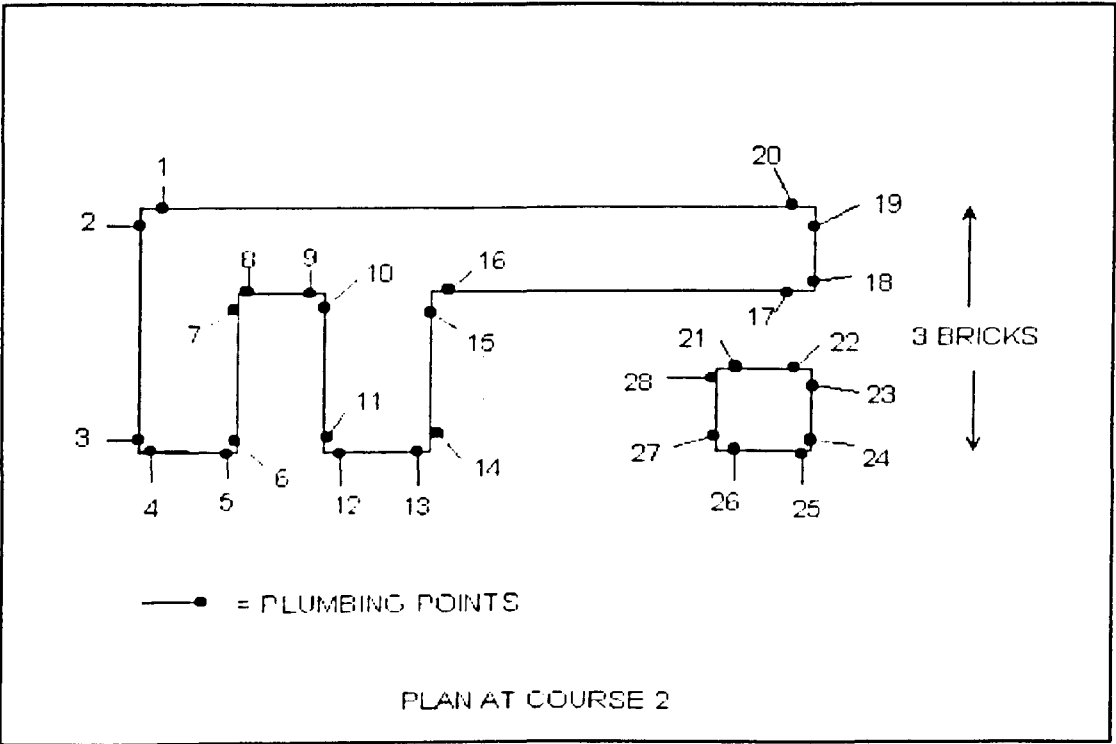


Figure 73. Plumbing points at course 2: stage 2 model.

The work in chapter seven on overspill in the identification and counting of tolerance requirements would indicate actual placing times for student 3 as being higher in the region of plumbing points 6-11 and 21-28 (see Fig. 73). Plumbing points 6-11 are identified on the basis of involving rapid changes of direction (3 dimensional work), and being located within a confined space only one brick wide. Plumbing points 21-28 are identified on the basis of being isolated, for the first three courses, from the main structure, and therefore requiring a degree of projecting ability. Isolated one brick piers of the type represented by plumbing points 21-28 are also difficult features to construct in brickwork, as there is only one vertical joint per course to take up any variations in brick size.

Course	Explicit Monitoring (EM) Time. (std. mins.)	EM as % of Total Time	Productive Time (std. mins)	Total Time (std. mins)	No. of Times Level Used
1.	4.27	31.49	9.29	13.56	35
2.	3.66 (-14.29%)	27.81 (-11.69%)	9.50 (+2.21%)	13.16 (-2.95%)	27 (-22.9%)
3.	3.72 (-12.88%)	20.33 (-35.44%)	14.59 (+57.05%)	18.31 (+35.03%)	30 (-14.3%)
4.	3.90 (-8.67%)	24.56 (-22.01%)	11.98 (+28.96%)	15.88 (+17.11%)	22 (-37.1%)
5.	4.30 (+0.07%)	27.53 (-12.58%)	11.32 (+21.85%)	15.62 (+15.19%)	32 (-8.6%)
6.	7.44 (+74.24%)	33.71 (+7.05%)	14.63 (+57.48%)	22.07 (+62.76%)	48 (+37%)

Table 2. Unadjusted results for student 3 performance on stage 2 model.  
[Bracketed Figures ( $\pm\%$ ) Represent Variation Over Course 1]

8.1.1 *Stage 2 model results.* Table 2 presents the unadjusted results for the stage 2 model as constructed by student 3. It can be seen that explicit monitoring time is reasonably consistent until course 6, when both it and productive time increase significantly. Student 3 experienced problems in completing course 6, having to remove the entire section over the lintol and rebuild it. Some of these problems resulted from the student making an error in laying out the model. Instead of being 6.5 bricks long, the model was built as 6 bricks long, causing tolerance problems when placing the lintol. The student made a further error in that the eastern elevation of the model required brickwork from the pier to the main wall after course 3, a requirement which the student missed. General tolerance requirement theory suggests that the student increased the difficulty of the eastern elevation by not bridging the opening between the pier and the wall, as shown in the model drawing.

Productive time, however, varies considerably from course 2 onwards. When timing the video recording of student 3, the author noticed that the student had a tendency to stop and think when problems arose. As these problems were not definable as production problems, such as a shortage of bricks, the resultant stoppages were not deducted from productive time. The author suggests that student 3 found the projection ability requirements of the stage 2 model to be more demanding than his rating of the model's difficulty had indicated prior to attempting the model. As well as the errors discussed above, the student experienced a problem with the distance between plumbing points 8 and 9, resulting in delays whilst a brick was cut to fit. No cuts should have been required in this area of the model. Student 3 revised his rating of the

model's difficulty upwards after completing the model.

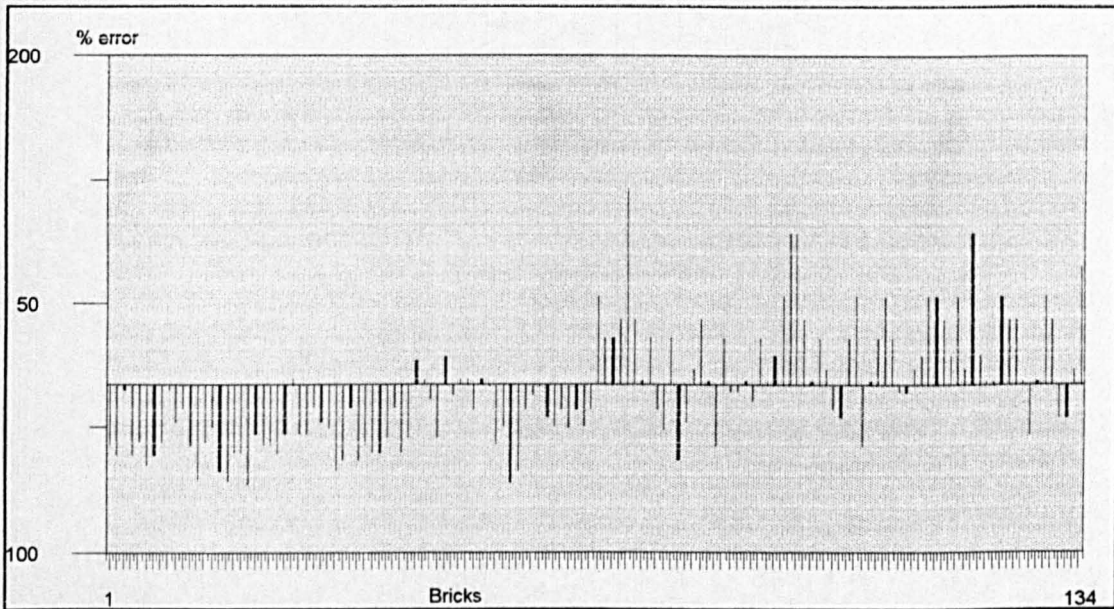


Figure 74. Error (%) of forecast placing time over actual placing time: experiment no. 2; stage 2 model, student 3.

## 8.2 Forecast placing times for stage 2 model.

The unadjusted data in Table 2 indicates that the student experienced particular difficulty in completing courses 3 and 6 of the model. Reasons for the extended production time on course 6 have been discussed above. The author can only suggest that the student perceived course 3 to present problems which the author was unaware of. Whilst the general tolerance requirement theory attributes a greater total for TR to course 3 (189.5) than either course 2 (161.5) or course 1 (165), the author suggests that a 12.92% increase in TR does not account for a 35.03% increase in total time taken for course 3 over course 1. The unadjusted data does not indicate that an acceptable correlation between forecast and actual placing times has been achieved with only 39.55% of forecast times being within specified limits.

PLUMBING POINTS.	BRICK No.	COURSE 1: PT.	C2 PT	C3 PT	C4 PT	C5 PT	C6 PT	STD. DEVIATION	MEAN	RANGE
(e) 5,6. (a) 3,4.	1	0.12 std. mins.	0.16	0.14	0.18	0.17	0.14	0.03	0.15	0.14-0.16
	2	0.09	0.13	0.15	0.10	0.12	0.13	0.02	0.12	0.11-0.13
(o) 19,20. (e) 1,2.	3 C.of D.	0.08	0.11	0.11	0.12	0.15	0.10	0.02	0.11	0.10-0.12
(e) 1,2.	4 C.of D.	0.09	0.10	0.11	0.12	0.13	0.10	0.01	0.11	0.105-0.115
	5	0.08	0.11	0.10	0.11	0.10	0.11	0.01	0.10	0.095-0.105
	6	0.10	0.11	0.10	0.07	0.08	0.13	0	0.10	0.10
	7	0.09	0.09	0.12	0.11	0.08	0.10	0.01	0.10	0.095-0.105
	8	0.10	0.10	0.10	0.15	0.11	0.14	0.02	0.12	0.11-0.13
(e) 19,20. (o) 17,18 / 19,20.	9	0.08	0.14	0.13	0.12	0.15	0.08	0.03	0.12	0.105-0.135
(o) 5,6.	10 Con'd	0.10	0.16	0.20	0.18	0.12	0.13	0.04	0.15	0.13-0.17
(a) 7.	11 Con'd	0.11	0.14	0.17	0.21	0.14	0.15	0.03	0.15	0.135-0.165
(a) 8. (e) 9	12 Con'd	0.12	0.09	0.25	0.12	0.18	0.15	0.06	0.15	0.12-0.18
(o) 9. (e) 10.	13	0.12	0.14	0.21	0.28	0.19	0.10	0.07	0.17	0.135-0.205
(o) 16. (e) 15.	14	0.08	0.12	0.12	0.20	0.12	0.11	0.04	0.13	0.11-0.15
(e) 16.	15	0.07	0.13	0.11	0.14	0.10	0.11	0.02	0.11	0.10-0.12
(o) 11,12.	16	0.18	0.13	0.13	0.11	0.24	0.15	0.05	0.15	0.125-0.175
(o) 10. (e) 11,12 / 13,14.	17 C.of D.	0.18	0.15	0.16	0.15	0.15	0.22	0.03	0.17	0.155-0.185
(o) 13,14	18	0.13	0.09	0.17	0.24	0.12	0.15	0.05	0.15	0.125-0.175
(o) 15	19 C.of D.	0.13	0.13	0.15	0.12	0.10	0.10	0.02	0.12	0.11-0.13
(e) 17,18.	20	0.13	0.15	0.14	0.16	0.12	0.11	0.02	0.14	0.13-0.15
(a) 21,22. (o) 27,28. (e) 23,24.	21 Iso'd	0.11	0.09	0.15	0.16	0.16	0.19	0.04	0.14	0.12-0.16
a) 25,26. (o) 23,24. (e) 27,28.	22 Iso'd	0.12	0.10	0.17	0.15	0.16	0.19	0.03	0.15	0.135-0.165
(((o)=odd courses, (e)=even, (a)=all)	23	n/a	n/a	n/a	n/a	n/a	0.14			
	24	n/a	n/a	n/a	n/a	n/a	0.09	KEY		
STAND'D DEVIATION		0.03	0.02	0.04	0.05	0.04	0.03	C.of D. = change of	Iso'd =	Bold Figures
MEAN		0.11	0.12	0.15	0.15	0.14	0.013	direction.	Isolated	= significant
RANGE (1 std.dev. around mean)		0.095-0.0125	0.11-0.13	0.13-0.17	0.125-0.175	0.12-0.16	0.115-0.145	Con'd = Confined		Pt errors.

Table 3. Unadjusted actual placing time results: student 3; experiment 2, stage 2 model.

CHARACT- ERISTIC	BRICK Nos.	PLUMBING POINTS	AVERAGE ERROR%	ERROR RANGE	WORST ERROR	BRICK Nos. FOR WORST ERROR
1. Enclosed / confined working space.	11, 12, 13.	7, 8, 9, 10.	30.04	63.64	-58.68%	13
2. Isolated work.	21, 22.	21-28 inc.	20.13	51.36	-35.00%	21
3. Change of working direction.	3, 4, 17.	1, 2.	23.75	54.758	-56.67%	17
OVERALL DATA			25.81	179.32	+119.86%	6.

Figure 75. Investigated brickwork characteristics specific data: stage 2 model.

Figure 75 shows that the least worst errors occurred on the 'isolated' characteristic. An important aspect of this error is that it, and the mean errors on the other characteristics, are negative errors. The forecast placing times are therefore almost consistently under-rating the time required on each brick. This was not expected within the context of student 3 exhibiting slightly slower placing times on panel 'A' than student 2, whose performance the forecasting equation is based on. The author suggests there is a significant difference between the expected under-rating (approximately 13% average) and the actual under-rating (approximately 26% average). In order to determine if this difference could be attributable to the data used to produce the forecast placing time equation, the author carried out a step-wise regression on the data utilising the current TR algorithm values. The strongest relationship remained that between the actual placing times for student 2 and the TR values on panel 'A'.

On this basis, there would be no benefit from revising the prediction equation pending further investigation into possible causes for the difference between actual and forecast placing times. The 'confined' characteristic is suggested as being the best example within the stage 2 model of how TR values can be affected by overspill from a number of components within the region of a particular characteristic, other than straight walling. This possibility is the starting point for further investigation of the forecasting errors.

*8.2.1 Possible factors influencing forecasting errors.* After reviewing the experiment data and the video recording of student 3 completing the stage 2 model, the author suggests two factors as being worthy of further investigation regarding a possible influence on the forecast placing time errors identified above. In previous chapters the gaining of expertise has been discussed, and it is that discussion which the author wishes to resume at this point.

*8.2.1.1 Influence of Increasing Expertise.* The author suggests that increasing expertise provides the ability to downgrade the emphasis placed on tacit monitoring, due to increased confidence in being able to regularly achieve the required placing accuracy. Within this scenario placing times should reduce with increasing expertise, subject to an overall limit on the speed of physical movement by the operative. This suggestion was discussed previously with regard to expertise certitude, when an exception to this general trend was noted as being the performance by student 3 on panel 'A'. The higher mean actual placing time for student 3 on panel 'A' should be considered in terms of the mean actual placing time achieved by student 3 on the stage 2 model (24.06%

slower than panel 'A' times). This suggests that the effect of expertise certitude has been completely eliminated by the increased production demands of model 2, as the average error in forecast placing times is 25.81%, indicating that student 3 is working at the limits of his expertise when completing model 2. Indeed, there is the possibility that student 3 is suffering from an expertise deficit in the region of an average 1.75%, and that any forecasting model based upon the performance of student 3 on model 2 would have to take this into account. Student 3 may actually be suffering some degree of error shock as discussed previously in the context of the performance by student 1 on panel 'B'.

Actual placing times are therefore dependant in part upon the expertise of the operative carrying out the task. Whilst it may be possible to build up data on operative performance in such a manner as to allow classification of operative expertise within a number of bands, ranging from novice to expert, and utilise this to forecast placing times for operatives of a given expertise level, such development lies outside the scope of this thesis. Given the intended use of the proposed ADA (comparing two or more versions of a design for buildability), the author suggests that such development is not essential for the ADA to produce useful data, so long as there is no intention to use the resulting forecast placing times within a programming context. On this basis, the author proposes that the forecasting equation;  $\text{Placing Time} = -0.0991 + \text{TR}(0.0253)$ , be used for the main body of the stage 2 model.

Data in Figure 75 shows that for the student with the greatest expertise, student



3, there is no exact relationship between mean TR value, and mean actual placing time.

MEAN TOLERANCE REQUIREMENT / COURSE	MEAN ACTUAL PLACING TIME / COURSE	VARIATION (±%) OVER COURSE 1	EXPLICIT MONITORING TIME VARIATION (±%) OVER COURSE 1	PRODUC- TIVE TIME VARIATION (±%) OVER COURSE 1
1 = 6.5	0.11			
2 = 7.6	0.12	+9.00	-14.29	+2.21
3 = 8.8	0.15	+36.36	-12.88	+57.05
4 = 10.4	0.15	+36.36	-8.67	+28.96
5 = 10.4	0.14	+27.27	+0.07	+21.85
6 = 10.0	0.13	+18.18	+74.24	+57.48
O'ALL =7.95	O'ALL =0.035	O'ALL =25.43	O'ALL =22.03	O'ALL =33.51

Figure 76. Production data related to TR values: stage 2 model; student 3.

8.2.1.2 Influence of Complex Setting-out Requirements. Panels 'A' and 'B' had no complex setting-out requirements, as they were intended to investigate the effects of increasing bonding complexity. The stage 2 model, however, has characteristics which result in complex setting-out requirements. These characteristics have been identified as 'confined' (Con'd), 'change of direction' (C.of D), and 'isolated' (Iso'd). Examination of the data on mean TR values and forecast placing times error, within each region of the model defined as one of the above characteristics, illustrates a possible trend; the performance of student 3 was generally slower, and more accurate, in the region of individual characteristics than was the case in the main body of the wall. Figure 77 illustrates the mean errors, allowing for negative values, for each characteristic in model 2.

	CORRECTED	AVERAGES	PER COURSE	(%)
Course	C.of D.	Conf'd.	Iso'd.	Straight.
1	-39.32	-34.80	-32.05	-37.92
2	-22.02	-33.97	+9.04	-33.18
3	-7.11	-43.94	-19.31	-13.77
4	+15.43	-14.50	na	+15.53
5	+6.54	-7.86	na	+23.92
6	+11.93	+19.70	na	+25.67
O'all	-5.76	-19.22	-14.11	-3.32

Figure 77. Corrected mean error per course: Model 2.

Examination of the full data shows that the regression equation [Pt = -0.0991 + 0.0253(TR)] consistently under-rated PT on all bricks in course 1. Course 1 had the lowest TR values; 6-7 per brick. It appears that the TR algorithm, which was developed to deal with bonding variations on the linear models (panels 'A' and 'B'), fails to deal with the implications of construction characteristics other than bonding. The characteristic of 'change of direction', as one example, can be argued to increase setting-out complexity as the number of occurrences of this characteristic increase within a design. The present algorithm does not recognise this, as it does not allow for the existence of what the author previously referred to as 'overspill' with regard to the calculation of TR values.

In order to determine the possible extent of overspill within the context of the stage 2 model, the author repeated the 'what if?' approach utilised previously to determine optimum TR values for panel 'B'. TR values for each brick on model 2 were adjusted until the error between forecast and actual placing times

fell within the boundaries of  $\pm 20\%$ . The author then examined the TR algorithm to determine which of the adjusted TR values could not be accommodated within a revised algorithm. Of the optimised TR values, thirty four (25.37%) could not be achieved on the basis of repeatable logic contained within a revised algorithm. Of these, two are marginally outside the specification at 20.54%. Given that the regression equation used as the basis for forecasting was based on a 70.2% level of correlation between placing time and TR value, the accuracy achieved by the final algorithm (74.63%) is sufficient. The author therefore suggests that whilst the revised TR algorithm does not give optimum results in all cases, it is sufficiently accurate for the purpose of demonstrating that the original TR algorithm is adequately versatile to accommodate changes in production characteristics resulting from various models. Figure 78 illustrates the final error values for model 2, and Figure 79 provides full data on final TR values and error levels.

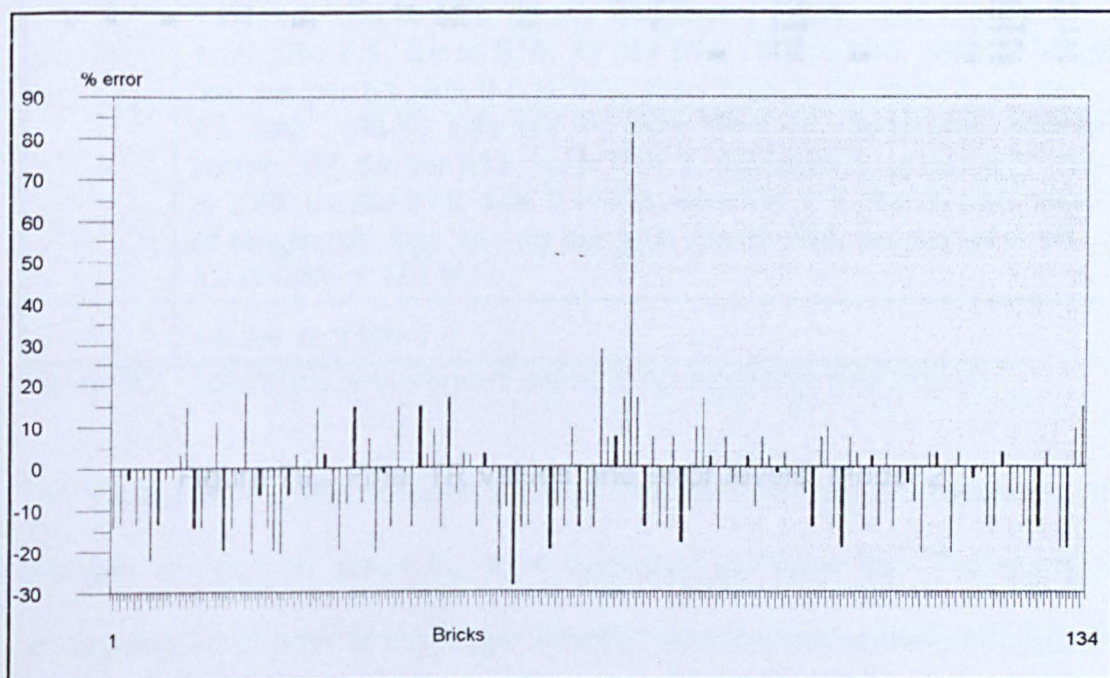


Figure 78. Final error values for forecast placing times: model 2.

Sick No	Tolerance Per Brick	Total Per Course	Forecast Pacing Time (std.mins)	Total Per Course	Actual Pacing Time (std.mins)	Error: Actual v. Forecast	Error: Percentage	Brick No	Tolerance Per Brick	Total Per Course	Forecast Pacing Time (std.mins)	Total Per Course	Actual Pacing Time (std.mins)	Error: Actual v. Forecast	Error: Percentage
01	8.5		0.11596		0.12	-0.00406	-1.37	04	10.5		0.15655		0.16	-0.01345	-7.47
2	7		0.073		0.09	-0.012	-13.33	3	9		0.1286		0.1	0.0286	28.50
3	7.5		0.06465		0.08	-0.01065	-13.31	4	9		0.1286		0.12	0.0000	7.17
4	7		0.078		0.09	-0.012	-13.33	5	9		0.1286		0.12	0.0000	7.17
5	7		0.078		0.08	-0.002	-2.50	6	9		0.1286		0.11	0.0186	16.91
6	7.5		0.06465		0.1	-0.00935	-9.35	7	9		0.1286		0.07	0.0586	83.71
7	7		0.078		0.08	-0.012	-13.33	8	9		0.1286		0.11	0.0186	16.91
8	7		0.078		0.1	-0.002	-2.50	9	9		0.1286		0.15	-0.0214	-14.27
9	7.5		0.06465		0.08	-0.01065	-13.31	10	8.5		0.14125		0.12	0.02125	17.71
10	8.5		0.11596		0.1	0.01596	15.95	11	10		0.1539		0.18	-0.0261	-14.60
11	8		0.1033		0.11	-0.0133	-14.75	12	10		0.1539		0.21	-0.0561	-36.71
12	8		0.1033		0.12	-0.0167	-13.92	13	9		0.1286		0.12	0.0086	7.17
13	8		0.1033		0.12	-0.0167	-13.92	14	10		0.1539		0.28	-0.1261	-45.04
14	7.5		0.06465		0.08	-0.01065	-13.31	15	10		0.1539		0.2	-0.0461	-23.05
15	7		0.078		0.07	0.006	7.17	16	9		0.1286		0.14	-0.0114	-8.14
16	9		0.1285		0.16	-0.0314	-19.63	17	10		0.1539		0.11	0.0439	39.91
17	10		0.1539		0.18	-0.0261	-14.50	18	10		0.1539		0.15	0.0039	2.50
18	9		0.1285		0.13	-0.0014	-1.08	19	10		0.1539		0.24	-0.0861	-55.87
19	10		0.1539		0.13	0.0239	18.28	20	10		0.1539		0.12	0.0339	28.25
20	9		0.1285		0.13	-0.0014	-1.08	21	10		0.1539		0.16	-0.0061	-3.91
21	9		0.1285		0.11	0.0185	16.91	22	10		0.1539		0.16	-0.0014	-1.08
22	9		0.1285		0.12	0.0065	7.17	23	10		0.1539		0.15	0.0039	2.50
23	8.5	178	0.14725	2.3232	0.16	-0.01875	-11.72	24	10.5	210	0.16655	3.1328	0.17	-0.00345	-3.23
24	8		0.1033		0.13	-0.0267	-20.54	25	9		0.1286		0.12	0.0000	7.17
25	8		0.1033		0.11	-0.0067	-6.09	26	9		0.1286		0.15	-0.0214	-14.27
26	8		0.1033		0.1	0.0033	3.30	27	9		0.1286		0.13	-0.0014	-1.08
27	8.5		0.11596		0.11	-0.0067	-6.09	28	9		0.1286		0.1	0.0286	28.50
28	8		0.1033		0.11	-0.0067	-6.09	29	9		0.1286		0.08	0.0486	50.75
29	8		0.1033		0.09	0.0133	14.78	30	9		0.1286		0.08	0.0486	50.75
30	8		0.1033		0.1	-0.0033	-3.30	31	9		0.1286		0.11	0.0186	16.91
31	8		0.1033		0.14	-0.02406	-17.11	32	8.5		0.14125		0.15	-0.00875	-6.82
32	9		0.1285		0.16	-0.0314	-19.63	33	10		0.1539		0.12	0.0339	28.25
33	9		0.1285		0.14	-0.0114	-8.14	34	10		0.1539		0.14	-0.0139	-9.92
34	9		0.1285		0.09	0.0385	22.95	35	10		0.1539		0.18	-0.0261	-14.50
35	9		0.1285		0.14	-0.0114	-8.14	36	10		0.1539		0.19	-0.0261	-19.00
36	9		0.1285		0.12	0.0065	7.17	37	9.5		0.14125		0.12	0.02125	17.71
37	8		0.1033		0.13	-0.0267	-20.54	38	9		0.1286		0.1	0.0286	28.50
38	9		0.1285		0.13	-0.0014	-1.08	39	10		0.1539		0.24	-0.0861	-55.87
39	10		0.1539		0.15	0.0039	2.50	40	10		0.1539		0.15	0.0039	2.50
40	9		0.1285		0.05	0.0385	22.95	41	10		0.1539		0.12	0.0339	28.25
41	9		0.1285		0.13	-0.0014	-1.08	42	10		0.1539		0.1	0.0539	53.90
42	10		0.1539		0.15	0.0039	2.50	43	10		0.1539		0.12	0.0339	28.25
43	9		0.1285		0.09	0.0385	22.95	44	10		0.1539		0.16	-0.0061	-3.91
44	9		0.1285		0.1	0.0033	3.30	45	10		0.1539		0.16	-0.0061	-3.91
45	10.5	199.5	0.16655	2.76805	0.1	0.0033	3.30	46	10.5	221.5	0.15655	3.32465	0.14	0.02655	19.95
46	9		0.1285		0.14	-0.0055	-8.99	47	9		0.1286		0.13	-0.0014	-1.08
47	9		0.1285		0.16	-0.0214	-14.27	48	9		0.1286		0.1	0.0286	28.50
48	9		0.1285		0.11	0.0185	16.91	49	9		0.1286		0.1	0.0286	28.50
49	9		0.1285		0.11	0.0185	16.91	50	9		0.1286		0.11	0.0186	16.91
50	9		0.1285		0.1	0.0285	28.60	51	9		0.1286		0.13	-0.0014	-1.08
51	9		0.1285		0.12	0.0065	7.17	52	9		0.1286		0.1	0.0286	28.50
52	9		0.1285		0.1	0.0285	28.60	53	9		0.1286		0.14	-0.0114	-8.14
53	9.5		0.14125		0.13	0.01125	8.55	54	8.5		0.14125		0.08	0.06125	75.55
54	10.5		0.16655		0.2	-0.03445	-16.73	55	10		0.1539		0.13	0.0239	18.25
55	10		0.1539		0.17	-0.0161	-9.47	56	10		0.1539		0.15	0.0039	2.50
56	10		0.1539		0.25	-0.0961	-38.44	57	9		0.1286		0.15	-0.0214	-14.27
57	10		0.1539		0.21	-0.0561	-26.71	58	10		0.1539		0.1	0.0539	53.90
58	10		0.1539		0.12	0.0339	28.25	59	10		0.1539		0.11	0.0439	39.91
59	10		0.1539		0.11	0.0439	39.91	60	9		0.1286		0.11	0.0186	16.91
60	10		0.1539		0.13	0.0239	18.25	61	10		0.1539		0.15	0.0039	2.50
61	10		0.1539		0.16	0.0139	10.36	62	10		0.1539		0.22	-0.0461	-23.05
62	10		0.1539		0.17	-0.0161	-9.47	63	10		0.1539		0.15	0.0039	2.50
63	10		0.1539		0.16	0.0039	2.50	64	10		0.1539		0.1	0.0539	53.90
64	10		0.1539		0.14	0.0139	10.36	65	10		0.1539		0.11	0.0439	39.91
65	10		0.1539		0.15	0.0039	2.50	66	10.5		0.16655		0.19	-0.02145	-12.34
66	10		0.1539		0.17	-0.0161	-9.47	67	10.5		0.16655		0.19	-0.02145	-12.34
67	10		0.1539		0.17	-0.0161	-9.47	68	10.5		0.16655		0.19	-0.02145	-12.34
68	10		0.1539		0.17	-0.0161	-9.47	69	10.5		0.16655		0.19	-0.02145	-12.34
69	10		0.1539		0.17	-0.0161	-9.47	70	10.5		0.16655		0.19	-0.02145	-12.34
70	10		0.1539		0.17	-0.0161	-9.47	71	10.5		0.16655		0.19	-0.02145	-12.34
71	10		0.1539		0.17	-0.0161	-9.47	72	10.5		0.16655		0.19	-0.02145	-12.34
72	10		0.1539		0.17	-0.0161	-9.47	73	10.5		0.16655		0.19	-0.02145	-12.34
73	10		0.1539		0.17	-0.0161	-9.47	74	10.5		0.16655		0.19	-0.02145	-12.34
74	10		0.1539		0.17	-0.0161	-9.47	75	10.5		0.16655		0.19	-0.02145	-12.34
75	10		0.1539		0.17	-0.0161	-9.47	76	10.5		0.16655		0.19	-0.02145	-12.34
76	10		0.1539		0.17	-0.0161	-9.47	77	10.5		0.16655		0.19	-0.02145	-12.34
77	10		0.1539		0.17	-0.0161	-9.47	78	10.5		0.16655		0.19	-0.02145	-12.34
78	10		0.1539		0.17	-0.0161	-9.47	79	10.5		0.16655		0.19	-0.02145	-12.34
79	10		0.1539		0.17	-0.0161	-9.47	80	10.5		0.16655		0.19	-0.02145	-12.34
80	10		0.1539		0.17	-0.0161	-9.47	81	10.5		0.16655		0.19	-0.02145	-12.34
81	10		0.1539		0.17	-0.0161	-9.47	82	10.5		0.16655		0.19	-0.02145	-12.34
82	10		0.1539		0.17	-0.0161	-9.47	83	10.5		0.16655		0.19	-0.02145	-12.34
83	10		0.1539		0.17	-0.0161	-9.47	84	10.5		0.16655		0.19	-0.02145	-12.34
84	10		0.1539		0.17	-0.0161	-9.47	85	10.5		0.16655		0.19	-0.02145	-12.34
85	10		0.1539		0.17	-0.0161	-9.47	86	10.5		0.16655		0.19	-0.02145	-12.34
86	10		0.1539		0.17	-0.0161	-9.47	87	10.5		0.16655		0.19	-0.02145	-12.34
87	10		0.1539		0.17	-0.0161	-9.47	88	10.5		0.16655		0.19	-0.02145	-12.34
88	10		0.1539		0.17	-0.0161	-9.47	89	10.5		0.16655		0.19	-0.02145	-12.34
89	10		0.1539		0.17	-0.0161	-9.47	90	10.5		0.16655		0.19	-0.02145	-12.34
90	10		0.1539		0.17	-0.0161	-9.47	91	10.5		0.16655		0.19	-0.02145	-12.34
91	10		0.1539		0.17	-0.0161	-9.47	92	10.5		0.16655		0.19	-0.02145	-12.34
92	10		0.1539		0.17	-0.0161	-9.47	93	10.5		0.16655		0.19	-0.02145	-12.34



STEP	ACTIONS REQUIRED (Artifact 2: model 2)
1.	Take plan view of wall, commence at first 'x' and 'z' axes intersection, take length 'z1', process as per algorithm 1, take length 'x1', process as per algorithm 1, repeat for all 'x' and 'z' intersections, 'x...n' 'z...n'. Record number of changes of direction, check for closure: 'z...n' = 'x...n' + 1.
2,3,4,5	As per algorithm version 1.
6.	<p>Take course 1, go to brick 1(first 'x','z' intersection), define TR as: 'x' axis, 1 (SP), 2 (HLS); 'y' axis, 1(HLL), 1 (BJT), 2 (HSL); 'z' axis, 1.5 (horizontal sagittal square), sum TR for brick 1(b1) = 8.5. Go to b2, take b1 value, subtract 1 (SP), 1.5 (HSS), add 1 (VJT), if penultimate brick on length 'z1' add 1 (further vertical joint), sum TR for b2 = 7. Repeat until final brick on length 'z1', b3, as per b1.</p> <p>Turn to 'x' axis (change of direction), on length 'x1' go to b4, as per b2 , sum TR for brick = 7, go to b5, as per b4, sum TR for brick = 7, go to b6; deduct 1 (HLS), add 1.5 (HLS - change over point, mid-course), sum TR for brick = 7.5, repeat as b5 until penultimate brick (b8) on length 'x1'. Penultimate brick as per b7, plus one (further vertical joint), sum TR for brick = 8.</p> <p>Go to b9, change of direction, as per b8, plus 0.5 (HSS), sum TR= 7.5, b9 forms length 'z3'. Go to b10, as per b1, less 1.5 (HSS), plus 1 (HSS), sum TR= 8. Go to b11, as per b10, less 1 (vertical joint), add 1 (HLS), sum TR= 8. Go to b12, start of length 'x3', as per b11, sum TR= 8. Go to b13, as per b12, sum TR= 8.5. Go to b14, as per b13 less 1 (HLS), add 0.5 (HLS) sum TR= 7.5. Go to b15, as per b14. Go to b16, start of length 'z4', as per b1 plus 0.5 (HSS), sum TR= 9. Go to b17, as per b2, add 1 (HLS), add 1(VJT), sum TR = 10. Go to b18, start of length 'z5', as per b16, sum TR= 9. Go to b19, as per b17. Go to b20, as per b15, add 2 (VJT), sum TR = 9. Go to b21, start of length 'z6' and 'x5', as per b16. Go to b22, as per b21. TR for course = 174.5.</p>
7, 8	As per algorithm 1.

Figure 80. Tolerance requirement calculation algorithm (version 3).

The TR algorithm, after revision to accommodate TR overspill resulting from changes of direction, takes the form illustrated in Figure 80. The reader is recommended to refer to the stage 2 model layout whilst working through the

TR calculation algorithm at Figure 80.

### 8.3 Conclusions.

The following conclusions can be drawn from the work discussed in this chapter:

- \* The complexities of brickwork production are such that a single linear relationship, as is found in the original forecast placing time equation, between tolerance requirements and placing time can adequately represent various production characteristics, only through a versatile algorithm capable of recognising, and responding to, such characteristics.
- \* Operative expertise varies with individual operatives. For programming purposes this would raise problems as the actual expertise of operatives would not be known at the time of forecasting. For buildability assessment, however, this is not a significant problem as the emphasis is on variations on a given design, rather than on variations in the performance of operatives constructing that design.
- \* TR overspill occurs in the region of individual brickwork characteristics such as 'change of direction', 'confined', and 'isolated' work.
- \* TR overspill appears to be best dealt with in forecasting placing times by increasing TR values in specific regions of the task concerned

through the application of an appropriate algorithm

- \* The effect of TR overspill on actual placing times appears to diminish in a non-linear manner from the second course of brickwork onwards.
- \* The data suggests that as operative expertise increases, the operative concerns him/herself less with achieving placing accuracy and more with planning ahead. This manifests itself as unproductive periods where the operative appears to concentrate on decisions regarding future actions.
- \* A further consideration is the relationship between error shock and expertise certitude, in that the results of these factors occurring may be the same, but the cause of each is completely different.
- \* The experimental work has indicated a need for the forecasting equation to be versatile in responding to varying production characteristics. The author suggests that this need will require the TR algorithm to be versatile in the manner utilised for searching CAD file data on designs. Without this versatility important characteristics of the CAD design may be missed, and an inaccurate buildability assessment will result.

## 9. CONCLUSIONS AND FURTHER RESEARCH.

*From yo-yos to skyscrapers, all man-made objects are the result of some person's or some group's decision as to their use and appearance. The inescapable planned decisions of others surround, direct, aid, or hamper us in our daily lives. Accidents are the only exception.*

Wilson (1979)

### 9.1 Conclusions.

In the early stages of this thesis the following hypothesis was stated:

*The production of a skill modelling based Automated Design Aid, to be used at sketch design stage, and within a CAD environment, would allow task level buildability to be improved through a simplification strategy managed by the communication of appropriate knowledge from construction process workers to design process workers.*

In testing the hypothesis a number of conclusions have been reached. During the discussion of these conclusions the reader may find reference to Figure 81, a variation of which appears in the introduction as Figure 'A', of use.

- \* The proposed automated design aid (ADA) would have to operate in a highly fragmented UK construction industry which faces many diverse problems in achieving an efficient production process.
- \* No single approach to buildability can realistically be expected to solve such a diversity of problems, as shown by the failure of over-ambitious approaches in the past. The design aid proposed within this research is focused solely at one aspect of fragmentation: the problem of the design process being separated from construction process knowledge.



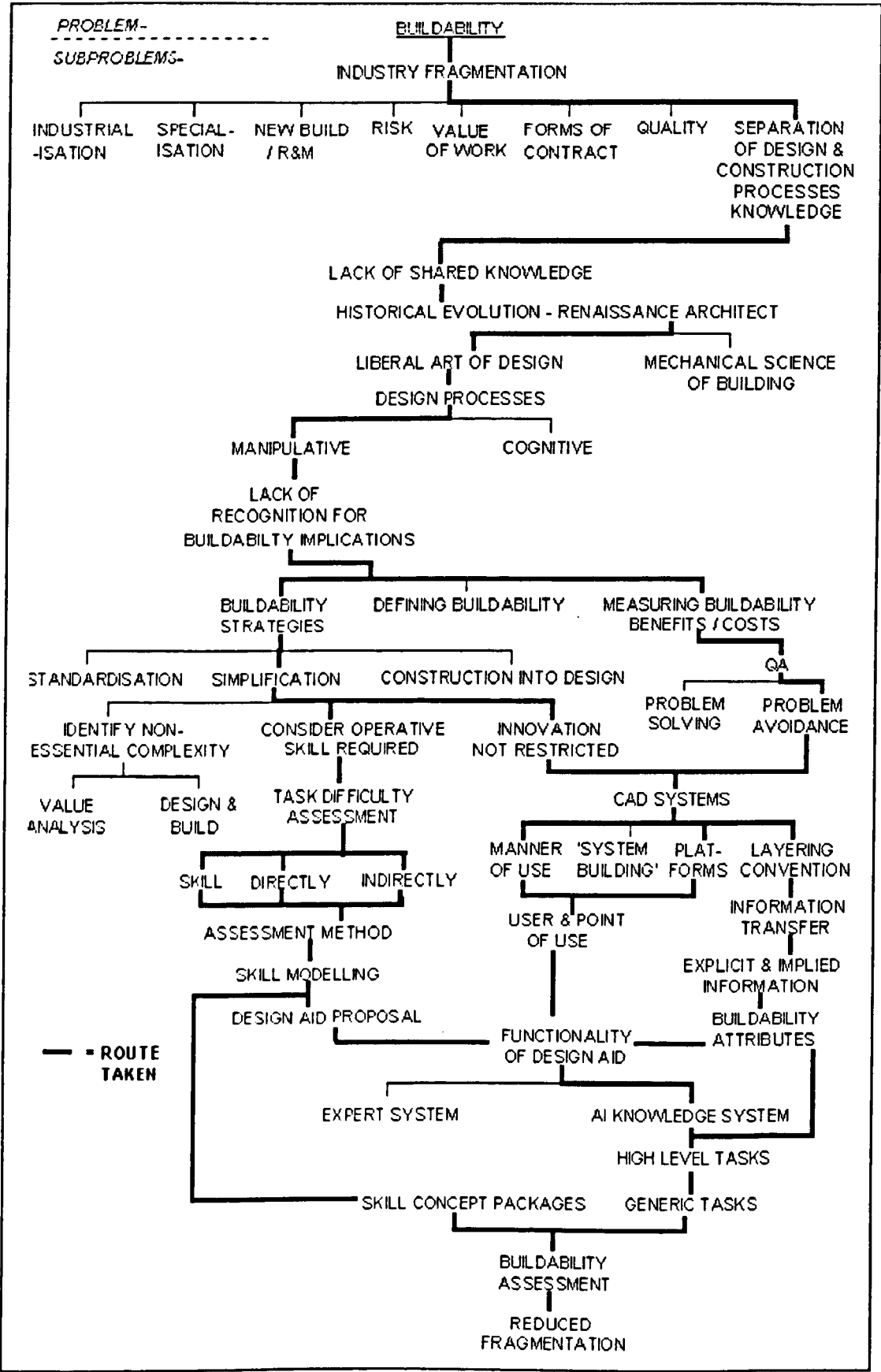


Figure 81. Route, representing a contribution to reduction of fragmentation in the UK construction industry, through the key subject areas of the thesis.

- \* Historical reasons for the separation of the design process from construction process knowledge have been identified. The origin of the problem is the evolution of the architect as a practitioner of the liberal art of design from the Renaissance onwards. This evolution, and the attendant problems for the production process, was effectively constrained by the narrow nature of the industry (a limited range of materials and techniques were available to the architect) until the 19th. century, when new materials and technologies began to appear ever more rapidly. The pattern of the architectural profession's development over several hundred years has contributed to the modern-day need to consider buildability explicitly, rather than implicitly.
- \* Contemporary design processes have largely failed to deal with the separation problem, in that they devalue the building phase of the construction process. The building phase effectively becomes merely an opportunity to finalise the alterations in the design concept. Such alterations may not occur as a response to knowledge concerning the process of construction, rather than design.
- \* Construction technology solutions have not been any more successful in overcoming the separation problem than have contemporary design processes. This is mainly due to their being seen by design process workers as imposed solutions to the design problem, which do not allow the designer to practice creativity (the balancing of convergent and divergent responses) in reaching a solution to the design problem.

- \* The manner of the architectural profession's evolution has contributed to the current situation where it is seen as being necessary to reduce the number of failures in the construction industry, which may be done in part by a clearer understanding of the significance of the construction process's evolution.
- \* A significant role of buildability is seen as being one of overcoming separation through communicating relevant knowledge of construction processes to design process workers. Three strategies for buildability have been identified; simplification, standardisation, and construction into design. Of these, simplification has been found to have the greatest potential value in communicating knowledge. However, buildability strategies are not seen as being mutually exclusive in principle, and it is possible for them to be used in conjunction.
- \* Quality assurance (QA) systems cannot be seen as appropriate solutions to the separation problem, as QA only ensures conformance to a specification. No specifications exist for the reduction of separation, or the achieving of buildability. Design and build contracts are also not seen, at present, as being effective contributors towards reducing the separation problem. This is due to a variation of the separation problem, whereby contractors do not have sufficient design skills to cut costs through the use of design.
- \* A contribution towards reduction of the separation problem must

therefore not impose technological solutions on the design process whilst allowing the design process worker access to relevant construction process knowledge. The proposed ADA seeks to operate within the existing design technology of CAD systems, and does not seek to impose any given construction technology or method. No existing design aids are capable of this.

- \* The functionality of the proposed ADA is constrained by the nature of the adopted design technology environment in that only explicit, objective data is held within CAD systems. The proposed ADA seeks to operate on the basis of objective data only.
- \* A preferred point of use has been identified for the proposed design aid through the application of value engineering principles. These indicate that buildability strategies are best implemented during the earliest design stages. The proposed design aid is intended for use at the sketch / briefing stage of design. This decision is supported by the recommendation of Working Group 11 regarding buildability, which is to encourage the early use of appropriate expertise/methodology.
- \* The main implication of the preferred point of use decision is the relative lack of detail available; the scale of drawings representing the data to be analysed by the design aid will typically be 1:100 or greater. The basis of buildability assessment therefore has to be capable of processing small amounts of explicit data in such a manner as to increase the

amount of 'knowledge' concerning the design. This additional knowledge is referred to as 'implied' knowledge.

- \* The role of separators/occupants, adjacency, and buildability attributes such as tolerance requirements, as sources of implied data concerning the design were noted as being relevant to the operation of the proposed design aid in conjunction with a CAD system.
- \* Such processing has to contend with the problems of adding intelligence to CAD systems: information poor nature of artifacts; difficulty linking reasoning agents to resource demanding CAD systems; lack of a co-operative model allowing interacting multiple agents within a CAD environment. No existing CAD 'add-ons' have been identified as being currently capable of assessing a design for buildability.
- \* AutoCAD has been adopted as the CAD package with which the prototype ADA is intended to operate. DXF/DXB files have been identified as a possible basis for the interchange of data between AutoCAD and the design aid.
- \* The key area of what forms relevant knowledge for the design process worker regarding the process of construction has been identified as being knowledge related to identifying the difficulty of constructing a given design on-site. This knowledge is summarised in terms of operative skill, which allows a basis for assessing a design in terms of

task difficulty. Task difficulty is taken as reflecting buildability; the more difficult the task, the worse the level of buildability.

- \* No methods for direct assessment of difficulty involved in the completion of construction tasks were identified. None of the methods of assessing difficulty of work in other industries, such as design for assembly (DFA), were found to be directly transferable to the assessment of difficulty in construction work.
- \* The work with the most potential as a basis for the assessment of construction task difficulty is that of Welford, with particular reference to the use of accuracy, competence and rapidity in defining and measuring skill. Skill concept packages are identified as one possible means of assessing task difficulty through consideration of the skill required to complete the task.
- \* Particular reference has been made to the problems of using expert systems for both the design and buildability problems. An alternative approach, in the form of an ADA utilising four modules based on the generic task (GT) philosophy, is proposed. A GT approach relies upon a level of artificial intelligence (AI) being achievable without the use of dedicated AI machines or software.
- \* The concept of high level tasks, within which exist various generic tasks, provides the basis for the work analysis of a given design by identifying

the range of high level tasks required to construct the design. The construction problem represented by the design can then be decomposed into a series of subproblems; the artifacts to be constructed by each of the high level tasks. Skill concept packages are utilised to identify implied knowledge regarding each artefact, such as the tolerance requirements per course of brickwork in a given wall. All the implied information on each artefact can then be brought together to provide an overall assessment of task difficulty.

- \* Tolerance requirements have been shown to be a potential basis for the assessment of task difficulty within the context of brickwork as a high level task. This is through their use in the forecasting of placing times as an indicator of task difficulty. The manner in which tolerance requirements are identified and counted has a significant effect upon the accuracy of forecast placing times. An algorithm for the tasks of identification and counting tolerance requirements has been developed.
- \* Observing and timing actual placing times has been shown to be an activity within which observer expertise is important. A definition of that which constitutes a placing movement has been produced as a basis for guiding potential observers.
- \* A mathematical representation capable of forecasting placing times as a response to tolerance requirement values within a given brickwork design has been developed by this research.

- \* Versatility is required in the tolerance requirement algorithm's approach to the searching of CAD files for buildability data. Complex relationships have been identified between tolerance requirements and specific characteristics of brickwork construction. Tolerance requirement overspill, as one example, occurs in the region of individual brickwork characteristics such as 'change of direction', 'confined', and 'isolated' work. Tolerance requirement overspill appears to be best dealt with in forecasting placing times by increasing tolerance requirement values in specific regions of the task concerned. The effect of tolerance requirement overspill on actual placing times appears to diminish in a non-linear manner from the second course of brickwork onwards.
- \* A single linear relationship, as is found in the original forecast placing time equation, between tolerance requirements and placing time can adequately represent the response of a range of operatives only through the use of an algorithm which can recognise, and appropriately respond to, production characteristics such as 'change of direction', 'isolated', and 'confined'.
- \* Operative expertise varies with individual operatives. For buildability assessment this is not a significant problem as the emphasis is on assessment of variations on a given design, rather than on variations in the performance of operatives constructing that design. As operative expertise increases, the operative apparently concerns him/herself less with achieving placing accuracy and more with planning ahead. This



manifests itself as unproductive periods where the operative appears to concentrate on decisions regarding future actions.

- \* The experimental work has indicated a need for the forecasting equation to be versatile in responding to varying production characteristics. This need will require the tolerance requirement algorithm to be versatile in the manner utilised for searching CAD file data on designs. Without this versatility important characteristics of the CAD design may be missed, and an inaccurate buildability assessment will result. Such versatility indicates the need for an artificial intelligence approach, which the generic task theory is suited for.

## **9.2 Application of the conclusions.**

By emphasising the management of information, in the form of explicit and implied information, the proposed design aid takes a radically different approach to buildability from previous buildability strategies. The use of skill models is a manifestation of this approach. However, there was no intention within this thesis to develop a full range of skill models; the intention being purely to test the hypothesis that such models are both possible to construct, and relevant to the assessment of buildability. The results of the research undertaken exhibits that such models are possible, and that they can make a contribution towards reducing separation within the UK construction industry.

An important aspect of this work is that skill modelling appears to be possible with respect to any high level task to which general tolerance requirement

theory can be applied. As the general theory defines tolerance requirements with respect to locating task elements within three dimensional space, this suggests that it can be applied to any production situation wherein the product is a three dimensional artifact. Such artefacts are not solely produced by the construction industry. The concept of assessing task difficulty through the use of skill models based upon general tolerance requirement theory therefore emerges as possibly being generic to all industries.

A further consideration is that the basing of buildability assessment on general tolerance requirement theory may prove effective in 'future-proofing' the design aid against changes in the nature of the construction industry. Recent attempts to industrialise the construction process, such as the ongoing Integrated Manufacturing Initiative (IMI) which seeks to transform the construction industry into a manufacturing industry, will inevitably change the nature of skills required by industry operatives. Skill modelling of the form proposed in this thesis could accommodate such changes by revising the 'rules', held within the competence component of the skill model, governing the production process, combined with adjustment of the tolerance requirement equations to reflect new production methods.

An example of the above approach can be found in the consideration of building forms utilising many different materials and production methods (high level tasks). The research completed thus far suggests that the buildability attribute of 'interfacing' will be of particular importance in the assessment of such buildings for buildability. The number of skill models required to assess

such a building (one per high level task) will present particular problems with regard to the manner in which each skill model deals with those locations within the building design which represent an interface between two or more high level tasks. It is suggested that these problems may be dealt with by developing skill model competence components which are aware of each others interfacing requirements. Competence components will therefore be required to exhibit high levels of flexibility.

The primary objective of this research was to descry a possible means of aiding the design process worker to determine the role of on-site production processes in providing a product which meets user requirements safely. The production of a skill modelling based automated design aid, to be used at CAD design stage, would allow task level buildability to be achieved through managing the communication of appropriate knowledge from construction process knowledge workers to design process knowledge workers, ie simplification. This thesis has therefore addressed all of the objectives set out in the introduction, and the hypothesis restated at the beginning of this chapter is therefore suggested as being correct. It now remains to summarise the suggested areas for further research in developing the design aid to the prototype stage.

### **9.3 Areas for further research on, and development of, the prototype ADA.**

The following are areas suggested as being relevant for further research regarding the development of the proposed automated design aid to the prototype level.

- \* Separators, occupants, and fields of relevance (see chapter four): a line can be deemed to be performing one of two functions; it is either defining a distance which separates two points, or it is defining a feature which is an occupant between two points. The research has shown that tolerance requirement overspill can be identified with respect to certain forms of occupant lines, ie the brickwork characteristics of 'confined' etc. (see chapter eight). The extent of any field of relevance around occupant and separator lines needs to be established through further research. The indication thus far is that fields of relevance with respect to brickwork characteristics do not have an extensive effect on task difficulty.
- \* Figure 29 illustrated a possible link between Ferguson's hierarchy of buildability and the author's suggested attributes for use by the proposed ADA in buildability assessment. Further investigation of such a link, particularly within the context of module 'C's functionality regarding the pre-prototype skill model for the high level task of bricklaying, may be of assistance in establishing a check for the manner in which CAD file data are processed by the ADA. This would be particularly helpful as an early check during the development of the full complement of suggested buildability attributes.
- \* This research has focused particularly on the buildability attribute of tolerance requirements. The role of the remaining attributes regarding the assessment of task difficulty, and their roles with respect to each

other within the prototype level design aid, also need to be researched further. This is an important precursor to the development of additional skill models covering high level tasks other than bricklaying. Such further research is suggested as requiring a number of different designs, which do not replicate those utilised by this research, to be evaluated, so as to check each of the buildability attributes utilised by the ADA for consistency across varying production situations.

- \* A requirement for the operative to undertake tacit monitoring has been shown to slow the rate of production (see chapter seven). All that can presently be stated on this point is that, on the basis of the recorded data, increasing expertise seems to reduce the slow-down effect of tacit monitoring. However, the precise nature of the interaction between tacit monitoring and rate of production is suggested as being relevant to the accuracy of the buildability assessment achieved by the design aid. A thorough investigation of this interaction's nature is suggested as a possible area of further research .
  
- \* A possible link between placing times followed by explicit monitoring and personality aspects of individual operatives has been suggested. This area may be formalised for further research in terms of the planning action(s) undertaken by the operative during the process of production (see chapter eight). This should be particularly considered with regard to the commonly held belief that increasing operative expertise results in a directly proportional increase in productivity. The data in this

research suggests that the relationship between productivity and expertise is somewhat more complex than a simple directly proportional one.

- \* Within the development of expertise, the influence of error shock and expertise certitude have been noted, as has the fact that both appear to have similar effects on recorded time data. Further research could usefully be focused on determining more precisely the circumstances under which each could be expected to occur.
- \* It has been suggested that development work to this point does not indicate any significant benefit arising from the application of systems theory within the prototype, single high level task based, ADA. However, systems theory may provide a vocabulary for the process of assessing more than one high level task within later versions of the design aid which will hold more than one skill model. A particular area of relevance for such a vocabulary is suggested as being control of two or more skill models at their interface within a design. Such a systems based vocabulary will require further research to validate.
- \* A possible relationship between tolerance requirement overflow and cascade processing has been identified. Examination of such a relationship is suggested as a possible area for further research in order to determine the existence of any significant connection with the proposed buildability assessment methodology.

- \* Buildability assessment values are not intended within this thesis to be viewed in isolation. However, such values may well be used to place the design portion which is being assessed at a particular point on a reference scale of absolutes ranging from poor to good buildability. Further research would be required to develop suitable reference points from which to produce such an absolute scale. A significant question is suggested a being whether or not good and bad buildability can be consistently established across more than one high level task. In other words, would an assessment value which indicates poor buildability with regard to a brickwork production task also indicate poor buildability in a plastering task?
  
- \* An important aspect of this work is that skill modelling appears to be possible with respect to any high level task which accepts general tolerance requirement theory. Determination of the actual extent of those high level tasks which will accept general tolerance requirement theory would be beneficial to the further development of the theory. Such determination would also aid in evaluating the concept of assessing task difficulty through the use of skill models based upon general tolerance requirement, as possibly being generic to all industries.

## REFERENCES

- AB (72): General Conditions for Building and Civil Engineering Works., Ministry of Public Works, Copenhagen.
- Adams, H. (1913): *Building Construction. Comprising Notes on Materials, Processes, Principles, and Practice.*, London, Cassell and Co. Ltd.
- Allsopp, B. (1962): *A General History of Architecture.*, London, Sir Isaac Pitman & Sons Ltd.
- Ashford, J. L., (1989): *The management of quality in construction.*, E, & F. N. Spon, London.
- Autodesk (1992): AutoCAD Customisation Manual., Autodesk, Surrey, June 1992.
- Autodesk (1993): Layer Naming Convention for CAD in the Construction Industry Version 2., Autodesk, Surrey, November 1993.
- Bailey, R.W. (1982): *Human Performance Engineering.*, Prentice Hall Inc. New Jersey.
- Barrington, K. (1960): *The development of the architectural profession in Britain.*, London, George Allen & Unwin Ltd.
- Barry, R. (1984): *The construction of buildings: Vol. 4.*, Granada Publishing, London.
- Benner, P. (1989): *From novice to expert.* Addison-Wesley Publishing, San Francisco, California.
- Bijl, A., Shawcross, G. (1975): "Housing site layout system", *Computer Aided Design*, 7, (1), Jan. 1975.
- Bilodeau, E. A, Bilodeau, I. M. (1969): *Principles of Skill Acquisition.*, Academic Press, London, 1969.
- Bowen, P.A., Erwin, G.J. (1990): "The impact of second generation expert systems on building design evaluations.", *Proceedings, International Symposium on Building Economics and Construction Management*, pp 419-427, CIB, Sydney.
- Briggs, M. S. (1974): *The architect in history.* New York, De Capo Press.
- Brogan, D. (1988): Visual Search. *Proceedings of First International Conference on Visual Search*, University of Durham, September 5-9 1988, Taylor & Francis, London. 1988.



BRS (1970): Current Paper 25/70 "The use of cranes on low-rise, high density industrialised housing.", Building Research Station, Watford.

Building (1995a): "No more room at the top.", Editorial, 8 December 1995, London.

Building (1995b): "Study can help cut costs 15%", p.11, 8 December 1995, London.

Building Project Information Committee (1987): Production Drawings: a code of procedure for building works. London.

Burn, G. R. (1990): "Quality Function Deployment." in *Managing Quality*., Eds. B.G. Dale, J.J. Plunkett. Philip Allan Ltd.

CAD User (1993): "Brick Dimensions", pp 36-37, Cad-desk, Sept. 1993.

Carr-Saunders, Wilson (1933): in Barrington, K. (1960), p 23.

Cassidy, H.J. (1981): *Using Econometrics*., Reston Publishing Company Inc, Reston, Virginia.

Chaffin, D.B., Andersson, G. (1984): *Occupational Biomechanics*., Wiley Inc., New York.

Chandler, I. (1987): *Building Technology 3: Design, Production and Maintenance*. The Mitchell Publishing Company Ltd, London.

Chandrasekaran, B. (1983): "Towards a taxonomy of problem solving types.", AI magazine, pp 9-17, Winter/Spring 1983.

Chandrasekaran, B. (1986): "Generic tasks in knowledge based reasoning: high level building blocks for expert system design.", IEEE Expert, 1, (3), pp 23-30.

Chandrasekaran, B. (1987): "Towards a functional architecture for intelligence based on generic information processing tasks.", Proceedings Tenth International Joint Conference on Artificial Intelligence, Milan, August 1987.

Chandrasekaran, B. (1988): "Generic tasks as building blocks for knowledge based systems: the diagnosis and routine design examples." The Knowledge Engineering Review, 3, (3).

Chapman, N.F.S., Grandjean, C. (1991): *The Construction Industry and the European Community*., Oxford, BSP Professional Books.

CICA (1993): Building on IT For Quality., Construction Industry Computing Association, Cambridge.

CIOB (1988): Code of Estimating Practice, Supplement No. 2, Design & Build. Chartered Institute of Building, Ascot.

CIRIA (1983): Buildability: an Assessment., CIRIA Special Publication 26.

CITB (1995): Competence Requirements and Assessment Guidelines for Bricklaying (CONSTRUCTION) Level 2., CITB / City & Guilds Publication CNG 027/2.

Clarke, L (1983): "On the concepts of skill and training in the construction industry.", Proceedings 1983 Bartlett International Summer School, Geneva.

Clement, A., Lecland, P. (1994) "New Design Solutions With CATIA Solutions Version 4", *CAE News*, No.2, 1994, IBM Technology Solutions Europe Publication.

Construction Monitor (1994): Issue No. 7, Department of Environment, Nov. 1994.

Construction Monitor (1995a): Issue No. 9, Department of Environment, Feb. 1995.

Construction Monitor (1995b): Issue No. 12, Department of Environment, May 1995

Construction Monitor (1995c): Issue No. 16, Department of Environment, Oct. 1995

Coombs, P.N., Franks, J. (1990): "The expert system and its applications in the construction industry.", *Chartered Builder*, July/August 1990, Chartered Institute of Building, Ascot.

Craik, K.J.W. (1947): "Theory of the human operator in control systems I. The operator as an engineering system.", *British Journal of Psychology*, No. 38, pp 56-61.

Day, A. (1996): " The Maquette, the model and the computer: organisational futures for design and construction.", *Engineering Constructional and Architectural Management*, Oxford, Blackwell Science Ltd., pp 15 - 28, 3, (1 & 2), March/June 1996.

Designer (1996): *Designer v.3.52.*, Software Package for Ergonomic Design of Work Tasks, State University Kansas, 1996.

Downton, A. (1991): *Engineering the Human-Computer Interface.*, McGraw-Hill, London.

Dreyfus, H.L., Dreyfus, S.E. (1986): *Mind over machine: the power of human intuition in the era of the computer.* Basil Blackwell, Oxford, 1986.

Duchessi, P., O'Keefe, R.M. (1992): "Contrasting successful and unsuccessful expert systems.", *European Journal of Operational Research*, No. 61, pp 122-134, North-Holland Ltd.

Dudley, E., Jackson, C., Fletcher, E. G. M. (1961): "The Anglo-Saxon Priory Church at Deerhurst", In; *Studies in Building History.*, Ed. Jope, E. M., Odhams Press Ltd., London.

Eastman, C.M., Chase, S.C., Assal, H.A. (1993): "System architecture for computer integration of design and construction knowledge", *Automation in Construction*, Amsterdam, Elsevier Science B.V., 2, (2), (pp 95-108).

Emmerson (1962): Survey of problems before the construction industry., Ministry of Works, London.

Eysenck, M.W. (1994): *The Blackwell Dictionary of Cognitive Psychology.*, Ed. M.W. Eysenck, Blackwell Publishing, Oxford.

Ferguson, I. (1989): *Buildability in practice.* Mitchell Publishing, London.

Firlej, M., Hellens, D. (1991): *Knowledge Elicitation, A Practical Handbook.* London, Prentice Hall International (UK) Ltd.

Fischer, M. (1991): "Constructability improvements for the preliminary design of reinforced concrete structures.", PhD thesis, Dept. of Civil Engineering, Stanford University, California.

Gilbreth, G. B., Gilbreth, L. M. (1923): "A Fourth Dimension of Skill for Obtaining the Best way to Work.", *Society of Industrial Engineers Bulletin*, 5, (12), 1923, Dept. of Publications, Chicago.

Gray, C. (1981): *An Analysis of The Preliminary Element of Building Production Costs.*, MPhil Thesis, University of Reading.

Gray, C. (1983): "Buildability - the construction contribution.", Chartered Institute of Building, Ascot.

Gray, C., Hughes. W., Bennett. J. (1994): *The Successful Management of Design.* Centre for Strategic Studies in Construction, University of Reading.

Harris, F., McCaffer, R. (1995): *Modern Construction Management.*, 4th. Ed, Oxford, Blackwell Science Ltd.

Harvey, R. C., Ashworth, A. (1993): *The Construction Industry of Great Britain*, Oxford, Butterworth-Heinemann Ltd.

Heap, A. (1987): *Improving Site Productivity in the Construction Industry.*, International Labour Office, Geneva.

Herbert, G. (1978): *Pioneers of Prefabrication.*, Baltimore, The John Hopkins University Press.

Higgin, G., Jessop, N. (1963): "Pilot study on communications in the building industry(1963)", The Tavistock Report, National Joint Consultative Council, reprinted 1965, London.

Hillebrandt, P. (1985): *Economic Theory and the Construction Industry*, 2nd. edn., London, MacMillan Press Ltd.

Illingworth, J. R. (1984): "Buildability - tomorrow's needs?" Building Technology and Management, Chartered Institute of Building, Ascot

Jay, T. A. (1981): *Time Study.*, Poole, Blandford Press.

JCT (80): Standard Form of Building Contract 1980 Edition, Private With Quantities., Joint Contracts Tribunal, RIBA Publications Ltd., London.

Johnson, M. H. (1991): "Late Medieval houses in Western Suffolk.", Medieval History, Headstart History, Bangor, 1, (3), pp 121-127.

Karger, D.W., Bayha, F.H. (1987): *Engineered Work Measurement.*, 4th. edition, Industrial Press, New York.

Kartam, N.A. (1996): "Making effective use of construction lessons learned in project life cycle.", Journal of Construction Engineering and Management, March 1996, American Society of Civil Engineers, New York.

Kayis, B., Iskander, P.A. (1994): "A three-dimensional human model for the IBM/CATIA system.", Applied Ergonomics, 25, (6), Butterworth-Heinemann Ltd.

Kelly, J., Male, S.(1993): *Value management in design and construction.*, E & F. N. Spon, London.

Kempen, A., Kok, H., Wagter, H. (1992): "Design Modelling", Automation in Construction, 1, (1), pp 7-14, Amsterdam, Elsevier Science B.V.

Knoop, Jones (1967): *The Medieval Mason.*, 3rd ed. Manchester University Press.

Kochan, A. (1991): "Boothroyd/Dewhirst - Quantify your designs.", Assembly Automation, 11, (3), pp 12-14, MCB University Press, Bradford.

Konz, S. (1990): *Work design:industrial ergonomics*, 3rd edition, Publishing Horizons Ltd, Scottsdale.

Konz, S. (1995): *Work design:industrial ergonomics*, 4th edition, Publishing Horizons Ltd, Scottsdale.

Krendel, E.S. McRuer, D.T.(1959): "The human operator as a servo system element. Parts I and II.", *Journal of the Franklin Institute*, No. 267, pp 381-403, 511-536.

Kroll, L. (1986): *The Architecture of Complexity.*, London, B.T. Batsford Ltd.

Latham, M. (1994): Constructing the Team. (The Latham Report), Construction Industry Board.

Lawson, B. (1986): *How designers think*, Architectural Press Ltd, London.

Leaney, P. G, Wittenburg, G. (1992): "The evaluation methods of Hitachi, Boothroyd and Lucas." *Assembly Automation*, **12**, (2), (pp 8-17), MCB University Press, Bradford.

Lewis-Beck, M.S. (Ed.)(1993): *Regression Analysis.*, Vol. 2, Sage Publishing Ltd. London.

Liversidge, J. (1976): *Everyday life in the Roman Empire.*, B.T. Batsford Ltd., London.

Longmate, A.R., Welker, C. (1985): "Components of an industrial ergonomics program: The Johnson and Johnson experience.", In *Industrial Ergonomics: A Practitioner's Guide*, Alexander, D.C., Pulat, B.M. (Eds), Industrial Engineering and Management Press, Atlanta.

Lueprasert, K., Skibniewski, J. (1994): "Machine learning applications for automated constructability reviews." ASCE First Congress on Computing in Civil Engineering, Washington, Proceedings, (June 1994).

Macedo, M. C.(1978): *Value management for construction.*, John Wiley & Sons Inc., New York.

Macneil, J. (1994): "A mouse in the house.", *Building*, pp 47-48, 15 April, London.

McCloughlin, I. (1989): "CAD - The Taylorisation of office work.", *New Technology in Work Employment*, **4.**, (1), pp 27-39.

McLellan, A. (1990a): "BS5750 code reduces quality claims developer", *New Builder*, New Builder Publications Ltd, (8 February 1990).

McLellan, A. (1990b): "Standards body withheld critical BS5750 report", *New Builder*. New Builder Publications Ltd, (22 February 1990).

McLellan, A. (1990c): "BS 5750 Battle", *New Builder*. New Builder Publications Ltd., (22 February 1990).

Melville, I., Gordon, I. (1984): *The repair and maintenance of houses.*, London, The Estates Gazette Ltd.

Miller, E. J., Rice, A. K. (1967): *Systems of Organisation.*, Tavistock Publications, London.

Mitchell, J. W. (1977): *Computer Aided Architectural Design.*, New York, Van Nostrand Reinhold Company.

Moore, D. R. (1990): *Task difficulty and quality control*, BSc(Hons) Dissertation, Nottingham Polytechnic.

Moore, D. R. (1993a): "Buildability and skill concept packages: development of a possible design tool." Building Research and Information, London, E.& F.N. Spon, **21**, (2), (pp 117-121).

Moore, D. R. (1993b): " Development of Skill Models as an aid to buildability in design". Building The Future; ISE/BRE Int. Seminar, Brighton, Proceedings.

Moore, D. R. (1995): "Buildability: A Problem of Managing The transfer of Construction Process Knowledge.", Campus Construction, **3**, (2), Chartered Institute of Building, Englemere Services Ltd., Ascot.

Moore, D. R. (1996a): "Buildability Assessment And The Development Of An Automated Design Aid For Managing The Transfer Of Construction Process Knowledge.", Engineering Construction and Architectural Management, Oxford, Blackwell Science Ltd., pp 29 - 46, **3**, (1 & 2), March/June 1996.

Moore, D.R. (1996b): "Evolution of the architectural profession: a factor in the modern-day need to explicitly consider buildability.", Campus Construction, Englemere Services Ltd, Ascot, Spring 1996, **4**, (1), pp 13-17.

Moore, D.R. (1996c): "The Renaissance: the beginning of the end for implicit buildability.", Building Research Information, E&F.N. Spon, Paper accepted, publication 1996.

Moore, D.R. (1996d): "CAD systems: the opportunities and constraints for assessment of buildability within a cad environment.", Campus Construction, Englemere Services Ltd, Ascot, Summer 1996, **4**, (2)..

Moore, D. R., Ahmed, N. (1996): "Proposals for the development of an indigenous materials and methods orientated design data aid for design professionals practising in developing nations.", Habitat International, Sheffield, Paper to be published Sept. 1996.

Moore, D. R. , Tunnicliffe, A. (1994a): "AGES: An automated design aid (ADA) for improved buildability.", 11th Int. Symp. Automation and Robotics In Construction, Brighton, May 1994, Proceedings.

Moore, D. R., Tunncliffe, A. (1994b): "Creativity and Innovation in construction design: the effects of *Standardisation and Simplification*." , Paper in draft form.

Moore, D. R., Tunncliffe, A. (1995): "An Automated Design Aid (ADA) for Constructability.", Proceedings of the Second ASCE Congress on Computing in Civil Engineering, Ed. J.P. Mohsen, Atlanta.

Morgan, M. H. (1960): *Vitruvius The Ten Books on Architecture*., Dover Publications Ltd., New York.

Morizet-Mahoudeaux, P. (1991): "A hierarchy of network-based knowledge systems.", IEEE Transactions on Systems, Man, and Cybernetics, **21**, (5), Sept/Oct. 1991.

MTM (1996): Methods Time Measurement, MTM Association Ltd., Northwich.

Ndekguri, I., Turner, A. (1994): "Building Procurement by Design and Build Approach.", Journal of Construction Engineering and Management, ASCE, **120**, (2), June, New York.

Neale, R., Price, A., Sher, W. (1993): Prefabricated Modules in Construction., Chartered Institute of Building, Ascot.

NEDO (1988): Faster Building For Commerce., London, National Economic Development Office.

Negroponte, N. (1973): *Computer Aids in Design and Architecture*., N. Negroponte ed., New York, Petrocelli/Charter.

New Builder (1994): "D&B Forum Woos CIC.", New Builder, 25 November, London.

Newman, W. N. (1966): "An Experimental Program for Architectural Design", Computer Journal, **9**, pp 21-26, 1966.

Norros, L., Ranta, J., Wahlström, B. (1982): "On the modelling of the human process operator." Proceedings IFAC Conference Analysis, Design and Evaluation of Man-Machine Systems (pp 55-62), Eds. G. Johannsen and J.E. Rijnsdorp, Pergamon Press Ltd., Baden-Baden FRG.

Pateman, J. (1992): "A culture of customer satisfaction.", Chartered Builder, May 1992, Chartered Institute of Building, Ascot.

Pohl, J., Myers, L. (1994): "A Distributed Cooperative Model For Architectural Design", Automation in Construction, **3**, (2-3), July 1994, Amsterdam, Elsevier Science B.V.

Poulton, E.C. (1974): *Tracking Skill and Manual Control.*, Academic Press, London.

Prince, M. D. (1971): *Interactive Graphics For Computer Aided Design.*, London, Addison-Wesley.

Pulat, B.M. (1992): *Fundamental of Industrial ergonomics.*, Prentice Hall International, New Jersey.

QLG (1995): Constructing Quality., London, Quality Liaison Group, Construction Sponsorship Directorate, Dept. of the Environment, Nov. 1995.

Radford, A.D., Mitchell, J.R. (1986): "Automated architectural detailing: a knowledge-based approach.", Proceedings CIB 86, pp 737-745, International Council For Building Research, Washington.

Rankin, I. (1982): Quality control and tolerances for internal finishes in building., Technical Information Service No. 2, CIOB, Ascot.

Raouf, A., Tsuchiya, K., Morooka, K. (1982): "Effect of task difficulty and angle in a positioning task involving symmetrical and asymmetrical motions" Int. Journal of Production Research, No. 20, (pp 768-776).

Raouf, A., Joseph. T.K., (1986): "A study of informational load and task difficulty.", *Kybernetics*, **15**, (2), pp 85-92, Thales Publication (W.O.) Ltd.

Raouf, A. (1991): "Computer-aided workplace design: applications in predetermined motion time systems.", *Work Study*, **40**, (4), pp 16-19, July/August 1991, MCB University Press, Bradford.

RIBA (1990): RIBA Survey of Computer Usage 1989., RIBA, London.

Richens, P. (1978): "The OXSYS system for the design of buildings.", Proceedings, CAD 78, pp 633 - 653, IPC Science and Technology, Guildford.

Richens, P. (1994): "Does Knowledge Really Help? CAD Research at The Martin Centre" *Automation in Construction*, **3**, (2-3), July 1994, Amsterdam, Elsevier Science B.V.

RICS (1979): UK and US Construction Industries - A Comparison of Design and Construct Procedures., Report by Department of Construction Management, University of Reading. Sponsored by RICS.

RICS (1991): "Contracts in use", *Chartered Quantity Surveyor*, RICS, **13** (5) pp 9-11, Jan. 1991.

Salisbury, F. (1990): *Architects handbook for client briefing.*, London, Butterworth Architecture Management Guides.



Schaefer, W. F. (1993): "Instruments for the management of knowledge", *Automation in Construction*, 2, (3), Amsterdam, Elsevier Science B.V.

Sellie, C. (1992): "Predetermined motion-time systems and the development and use of standard data.", In *Handbook of Industrial Engineering*, 2nd, ed., Salvendy, G. (ed.), New York.

Skitmore, M. (1989): *Contract bidding in construction.*, Longman Scientific & Technical, Harlow.

Smit, J. (1994): "Resolving Differences.", *New Builder*, 9/16 December, London.

Smith, M (1987): *Manual of British Standards in Building Construction and Specification*, 2nd Ed., Hutchinson Education, London.

Smith, M. P. (1993): *Sydney Opera House.*, Michael Pomeroy Smith Pty., Sydney.

Smith, T. R. (1906): *Architecture Gothic and Renaissance.*, London, Society For Promoting Christian Knowledge.

Strike, J. (1991): *Construction into design: the influence of new methods of construction on architectural design, 1690-1990.*, Butterworth Architecture, Oxford.

Sutherland, I. E. (1963): "Sketchpad: A Man-Machine Graphical Communication System", *Proceedings, 1963 Spring Joint Computer Conference*, Baltimore, Spartan Books.

The Banwell Report (1964): "The placing and Management of Contracts for Building and Civil Engineering work." Report of the Committee, HMSO,

Troup, J.D.G., Edwards, F.C., (1985): *Manual Handling: a review paper.*, Health and Safety Executive, HMSO, London.

Tunncliffe, A.J., Scrivener, S.A.R. (1991): "Knowledge elicitation in design.", *Design Studies*, Vol. 12, No. 2, April 1991, Butterworth-Heinemann Ltd, pp 73-80.

Walker, A. (1989): *Project management in construction.*, 2nd Ed., Oxford, BSP Professional Books.

Walton-Ely, J. (1977): "The rise of The Professional Architect in England", In: *The Architect: Chapters in the History of the Profession*. Ed. Spiro Kostoff, New York, Oxford University Press.

Welford, A.T. (1968): *Fundamentals of skill*. Methuen & Co. Ltd., 1968.

Welford, A.T. (1976): *Skilled Performance: perceptual and motor skills.*, Scott, Foresman and Company, Glenview, Illinois, 1976.

WG11 (1995): Working Group 11 1995 Progress Report, Construction Industry Board, London.

Wilkinson, C. (1977): "The new Professionalism in the Renaissance.", In; *The Architect: Chapters in the History of the Profession*. Ed. Spiro Kostoff, New York, Oxford University Press.

Wilson, F. (1979): *The Joy of Building: restoring the link between architect and builder.*, New York, Van Nostrand Reinhold Company.

Wilson, J.R., Corlett, E. N. (eds) (1995): *Evaluation of Human Work.*, 2nd. edn., Taylor & Francis Ltd., London.

Winch, G., Deeth, G. (1994): "Managing CAD in architectural practice", *Automation in Construction*, Vol. 2, No. 4, Amsterdam, Elsevier Science B.V.

Wittkower, R. (1988): *Architectural principles in the age of Humanism.*, Academy Editions, London.

Yamazaki, Y. (1992): "Integrated design and construction planning system for Computer Integrated Construction.", *Automation in Construction*, Vol.1 No.1, Amsterdam, Elsevier Science B.V.

Young, M. (1986): *Architectural and Building Design.*, William Heinemann Ltd., London.



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